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GREENHOUSES

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1. INTRODUCTION

Greenhouse structures were developed for crop production during periods when growing outdoors was not feasible. Historically, the greenhouse structure was designed to optimize the penetration of incoming solar radiation. This was particularly necessary in temperate climates such as Ontario because of low light intensities received during the winter months. Initially control of temperature, relative humidity, carbon dioxide levels and air movement in greenhouses was primitive. As plant growing practices improved, better control of the greenhouse environment became essential. Future developments of computer devices and structural improvements will permit even greater control of the greenhouse environment and ultimately higher productivity.

An understanding of many varied aspects is needed when considering greenhouse construction. For example, in highly specialized crop production all conditions must be controlled uniformly in every part of the greenhouse. Cold areas or pockets with insufficient air movement can cause undesirable responses in plant growth and should be avoided. In addition, it is important that a greenhouse grower be prepared to adjust crops or growing techniques in response to external forces such as imports, energy prices, new demands on the markets or new cropping techniques such as movable benches, substrate culture, nutrient film technique, and supplemental lighting.

The Canadian greenhouse industry (greenhouse vegetables and flowers) during the eighties have shown steady growth (Table 1) not only in growing area but also in total farm gate value (estimate for 1990 is 500 million $). While the greenhouse surface area doubled between 1978 and 1990, the revenue tripled during the same period. The more than proportional increase in the farm value is due to increased production through better space utilization, scheduling and supplemental lighting rather than to price increases received for the product. In Ontario, the surface area for greenhouse vegetables (tomatoes, cucumbers, and sweet pepper) represents about one-half of the total area covered. The floricultural industry (potted plants, cut flowers and bedding plants) represents the other half of the greenhouse surface area. The most common glazing materials for greenhouses are glass and double polyethylene.

Table 1. Greenhouse area and farm value for major production areas in Canada

	Area (m^2) 000,000			Farm Value ($) 000,000		
	1978*	1983*	1990**	1978	1983	1990**
Ontario	2.26	2.50	3.7	112.3	169.9	276.0
British Columbia	.53	.44	1.5	26.3	33.7	102.0
Quebec	.35	.46	1.7	18.0	26.5	130.0
Alberta	.17	.52	0.6	10.0	15.4	38.7
Man./Sask.	.05	.09	0.1	2.9	6.1	7.0
Maritimes	.22	.26	0.3	13.3	19.1	28.7
	3.58	4.27	7.9	182.8	270.7	582.4

**Source: Statistics Canada, Greenhouse Industry Catalogue 22-202.*
***Source: Private communications with extension personnel in different provinces.*

This publication is intended to provide basic information on structures, glazing materials, greenhouse environment, controls and cost/revenue estimates for greenhouse production in Ontario. Methods of construction and construction plans are beyond the scope of this publication; however, advice is available from extension personnel and through some universities. A list of supply companies is presented at the back of this publication.

2. GREENHOUSE STRUCTURE

Site Selection

Careful planning is essential for the successful operation of a greenhouse business. Selecting the correct site is of utmost importance in the planning stage since, once situated, most operations remain in their original location. Some of the major considerations include:

1. Distance to market This is important for both wholesale and retail growers. Some perishable crops (e.g. roses) are harvested every day while others are harvested every two, three or four days (chrysanthemums, tomatoes and cucumbers). Initial decisions must be made regarding what type of crop to grow, and transportation expenses to the market must be weighed against possible higher prices for land close to metropolitan areas. For retail growers, the location near a major road plus presence of competitors should be considered. Moreover, familiarity with the expansion potential of a nearby town may be a valuable asset.

2. Availability of services The presence of a natural gas line at the property boundary is very important. During the last several years natural gas prices have been very competitive with those of oil or propane. Annual heating costs ($80,000 to $200,000 per hectare for 1985) make this an important consideration. The possibility of having an alternate fuel source may prove invaluable in the future.

The availability of single- and three-phase electric power is a further consideration, especially as more electrically operated equipment such as fans, ventilators, supplemental lighting, circulating pumps, potting machines and possibly heat pumps and/or dehumidifiers are being installed in greenhouses.

In many areas of southern Ontario where there is no access to surface water (e.g. lakes and rivers), the grower has to rely on city or well water. Generally, city water is of adequate quality with soluble salts less than .75 mS/cm. Since well water may be of very poor quality and unsuitable for continuous irrigation, water samples should be tested for their suitability and a local extension specialist contacted for advice. In areas where no irrigation water is available, the use of a cistern or a pond for collecting and storing rainwater must be considered. It should be remembered that more water is used on a year-round crop than the amount of rainwater which is received on the roof of a greenhouse range. This means that an additional water source is required when using a cistern and collecting all the rain from the roof during the year. The annual transpiration of a year-round crop in a glasshouse is estimated to be about 800 mm of water, not taking into account any leaching.

3. Topography Topography may be a hindrance as well as an advantage. A level grade facilitates easy building and snow removal; however, such areas may also be exposed to cold winter winds. For soil-grown crops such as tomatoes, cucumbers, roses, chrysanthemums and carnations, a well-drained and structured topsoil will be of benefit. Soil amendment or substrate culture may overcome some poorly structured soils but is often costly.

4. Size Preferably the site should be large enough to allow future expansion. The average greenhouse operation is 4000 m^2 but a larger landbase is required. Information regarding zoning bylaws, building requirements, the agricultural code of practice and permits, etc., should be obtained for the particular township or region. Orientation of the greenhouse(s) depends to a large degree on property configuration.

5. Layout The layout of the range depends on whether freestanding and/or gutter-connected houses are used. Freestanding houses are very common for seasonal use (bedding plants, nursery) and where easy access by trucks or wagons is important. It provides a means of maintaining different climates and construction can be easily staged. The houses are usually not longer than 30 m or wider than 6.5 m. Gutter-connected houses are preferably built with a ridge length of 60-65 m with a central pathway width of 2.50-3.50 m. The length of the working benches or beds is then no longer than 30 m, which seems to be the optimal length for labor efficiency. Where possible, fans should be located on the leeward side of the greenhouse range, while the airflow for forced ventilation is to be parallel to the longitudinal axis of the beds or benches. The maximum length for a greenhouse for forced ventilation is also about 60-65 m.

Types of Greenhouses

There are approximately 10 major suppliers (Section 6), each providing one or more types of greenhouse. This section will discuss the most common structural types currently available.

Freestanding Greenhouses

The forerunner to the polyethylene greenhouse was completely wood-framed (Figure 1), and designed for a 12 x 30 metre sheet of polyethylene film attached to the side and gable ends by wooden laths. Subsequently, two layers of polyethylene were used to reduce heating costs. A small 50 W centrifugal blower (Figure 2) kept the two layers inflated at a constant static pressure, a technique that is still used today. This type of freestanding house has lost popularity since the end walls gradually warp due to the continuous pressure created by the plastic under tension, and the continuously high relative humidity within the house.

Figure 1. A polyethylene-covered wooden structure.

Figure 2. A centrifugal fan used to inflate the two layers of polyethylene.

Figure 3. A freestanding double polyethylene-covered greenhouse (gothic shaped metal frame).

The gothic or quoinset shaped house (Figure 3) is now the most commonly sold greenhouse. It is used primarily for overwintering nursery material or the growing of bedding plants. Its basic frame is constructed of hot-dip galvanized steel bows. The width of the house of 5.5, 6.1, 6.4, 7.3, 8.2 or 9.1 m, matching the available widths of polyethylene sheets.

Freestanding glasshouses are still built in Ontario. These houses are used primarily by tobacco growers to raise seedlings.

Uneven span greenhouses which have been built for solar projects ("Brace" design) are not popular due to their high costs and low light transmissivity and generally impractical from a labour efficiency point of view.

Gutter-connected Greenhouses

Increasing energy and labour costs have forced growers to build gutter-connected (ridge and furrow or multispan) units instead of freestanding greenhouses. This type of house reduces energy costs, because of the smaller exposed surface area per unit greenhouse floor space, and reduces labour cost because of reduced walking distances. Moreover, a more uniform environment can be maintained in these houses compared to freestanding units.

Increased snow load problems are likely in most gutter-connected greenhouses, hence, structural or other appropriate provisions have to be made. For example, excess snow in gutters may be melted by means of an additional heating line near the gutters. Experience has shown that this is usually adequate, although glass breakage does occur in extreme cases.

There are basically two designs of gutter-connected greenhouses:

1. The arched or gothic type with fiber glass or double polyethylene (Figure 4) as the covering material. These come in different widths: 4.9, 5.5, 6.1 and 6.4 m for covering with double polyethylene (tube) for the arched types. The gothic types are usually wider (11.0, 12.8 m) and are commonly built to allow easier run-off for the water condensate on the inner layer especially near the peak. Interlocking extrusion devices are used to fasten polyethylene to gutters or sides (Figure 5).
2. The conventional type with a peaked roof (Figure 6). Any glazing material can be used with glass, fiber glass and double acrylic panels being the most common ones. The majority of these houses have a roof slope of between 10.3 and 26.6 degrees (1:2 pitch). Widths vary from 3.2 to 14 m. Bay spacing ranges from 3 to 3.7 m depending on the requirements for structural strength. Pregalvanized or hot-dip galvanized steel (pipe shape or roll-formed) or aluminum is used for gutters, posts, rafters and purlins. To reduce maintenance and increase light transmission in glasshouses, glazing bars are made predominantly of aluminum rather than of wood.

Figure 4. A gutter-connected range with double polyethylene on roof and double acrylic (SDP) sidewalls.

Figure 5. An example of an aluminum interlocking extrusion device to fasten polyethylene.

Figure 6. A glass covered, gutter-connected range.

Glazing Materials

Selection of the proper glazing material is a difficult but important decision. The difficulties lay in the great number of available materials, all with their own specific properties. Most require "special" fastening devices and sometimes a unique framework.

The type of crop(s) to be grown often determines the choice of greenhouse and glazing material. It is well known that plant growth is determined largely by the amount of available light measured at crop level. Some crops such as roses, carnations, chrysanthemums and cucumbers require a high light intensity during the winter while light may not be as important for other crops mainly under spring conditions (bedding plants). Therefore the **optical properties** of light transmission characteristics are important criteria in selecting a glazing material. Since the light transmissivity of most glazing materials (except glass) may become reduced with age, it is necessary to know how well the glazing material will perform in 5-10 years.

Since greenhouses are heated for year-round production, the **thermal properties** are important from an operational and economical point of view. It is unfortunate, however, that well insulated glazing materials have a lower light transmissivity as well as create a higher relative humidity in the greenhouse environment. These factors have to be weighed against each other while the types of crop(s) to be grown should be considered as well.

Greenhouses are also intended to protect crops from outside weather conditions such as snow, hail, wind, sunlight and freezing rain. **Mechanical** properties

such as load bearing capacity (for snow load), impact resistance (hail), tensile strength and tear resistance (wind, ice and snow), ultraviolet resistance (sunlight), electrostatic (dust), flammability (fire), water vapor resistance (condensation between two glazing materials), weight and thickness (glazing bar) and thermal expansion (type of glazing bars) have to be considered for each specific site. Other significant considerations are the cost of the material and its longevity.

The following sections will discuss the three different properties (optical, thermal and mechanical) in more detail.

Optical Properties

At southern Ontario latitudes (42-44°NL), the amount of solar radiation during winter is considered to be the major factor limiting production. Thus, very few tomatoes or cucumbers are grown commercially during December and January, while some greenhouse flower crops are grown using supplemental lighting. It is, therefore, important to consider light transmission of greenhouse glazing materials.

Many conflicting reports have been published on light transmissivity of different materials. The different measuring techniques usually account for the discrepancies. Light transmission is defined as the ratio of light passed through a material and the original amount of light striking the outer surface, when that light is directed perpendicular to the material. For plant growth, light between 400 to 700 nM wavelengths is useful for photosynthesis. Light intensity is often expressed as watts per square metre (W/m^2) or Einsteins per square metre per second ($E/m^2/sec$) of photosynthetic active radiation (PAR).

Two major factors which determine transmissivity of glazing are the refractive index and the amount of light absorbed by the material itself. Theoretical calculations have shown that about 4% of the light is reflected at each glazing/air interface for glass. This means that the maximum light transmission for a single layer of material is about 92%. This explains why light transmission through a double-layered glazing material is considerably less than through a single layer of the same material with a total thickness equal to the double layers. The maximum theoretical transmission through a double-layered material such as glass would be 85%, indicating that the major loss of light is through reflection, not absorption. This also accounts for the relatively small difference in light transmission between 100 and 150 micron polyethylene films.

Another important factor when discussing light transmission is the distinction between direct light and diffuse light. Direct light usually comes from one source (e.g. sun), while diffuse light is that which comes from different directions through reflection off the ground or other particles in the air. The highest transmission which can be obtained through any transparent material occurs when the light is at a right angle (perpendicular) to the glazing material. If light comes from an angle other than 90 degrees to the glazing material, more light will be reflected and thus a lower light transmissivity will be observed. This also explains why the transmission for diffuse light (cloudy days) is lower than for direct light. Summary data for measured transmission values are given in Table 2.

Table 2. Light transmissivity (%) of rigid and flexible glazing materials*

	Perpendicular	Diffuse
Single glass (4mm)	89	83
Single glass coated with tinoxide (Hortiplus, 4mm)	79	68
Double glass (16mm)	81	71
Reinforced polyester (Fiberglass, Tedlar coated)**	84	76
Acrylic (SDP, 16mm)	84	75
Acrylic (triple layers, 32mm)	78	65
Polycarbonate (Qualex, 6mm)	77	68
Polycarbonate (Qualex, 8mm)	70	64
Single polyethylene (UV-stab., 180 micron)	87	77
Double polyethylene (180 micron)	77	62
Ethylene vinyl acetate (EVA - copolymer, 180 micron)	89	79
Polyester (Melinex, OW 175 micron)	85	78
Polyester (Melinex, 071-75 micron)	93	85
Polyvinyl fluoride (PVF, Tedlar, 100 micron)	90	82
Polyvinyl fluoride (PVF, Tedlar, 50 micron)	91	83
Polytetrafluorethylene (PTFE, Teflon, 50 micron)	95	88
Polyvinyl chloride**	88	78

**Source: IMAG, Wageningen, the Netherlands, measurements on new and dry materials only.*

***Estimated*

It should be noted that the transmission values refer to new materials. Polyethylene and fibreglass are noted for their reduced transmissivity with age due to photochemical reactions in the materials. This deterioration is primarily caused by the UV portion of the sunlight.

Moreover, light levels at plant level are never as high as quoted in Table 2.

Interference by structural members (glazing bars, gutters, heating lines) as well as water condensation on the inside, or dust particles on the outside of the glazing will further affect the light levels in the greenhouse. Reports indicate that water droplets on the internal surface of a house can reduce light transmissivity by as much as 10%. Average levels of 50 to 70% of ambient light are common in greenhouses at plant level.

Thermal Properties

There are three mechanisms by which heat is transferred through a material, namely conduction, convection and radiation. These distinctive mechanisms have been discussed more fully in OMAF Publication 65 *Energy Conservation in Ontario Greenhouses*. The combined effects of the above mechanisms is given by the U-value or the overall coefficient of heat transmission for a given material. These U-values are measured under standard laboratory conditions and have to be adjusted appropriately for greenhouse conditions. For instance, the effect of windspeed on both sides of the glazing material, the presence of radiative surfaces (steam pipes), weather conditions (cloudy versus clear sky) and condensation taking place on the inside of the material, are conditions unique to greenhouses and affect the actual U-value (Table 3).

Table 3. Heat transfer coefficients for several greenhouse materials

Materials	U-value [W/(m^2. °C)]
Glass, single layer, 3mm thick	6.45
Glass, double layer, 6mm air space	3.70
Glass, triple layer, 6mm air spaces	2.66
Polyethylene film, single layer	6.53
Polyethylene film, double layer, separated by air	(est.) 5.0
Fiberglass, flat (for corrugated, 15% more)	5.68
Double acrylic (SDP-16mm)	3.12
Coroplast (4mm thick polypropylene)	4.65
Glass and bubble film (12mm thick)	3.3

However, for a comparison of materials the U-value is a good indication of the prospective insulative properties of a glazing material. As an example, double-layered materials separated by a (dead) airspace greatly reduce the heat transfer through the material compared to when the two layers are compressed together (double polyethylene versus single polyethylene). Moreover, the effect of the glazing material and respective fastening devices must be considered on the air exchange rate of the greenhouse. The natural air exchange between the inside and outside of the greenhouse is not incorporated in the U-value of glazing material, but may constitute a substantial heat loss for a greenhouse (10-20%). As an example, a single sheet of polyethylene makes a greenhouse more airtight compared to a greenhouse covered with a large number of glass panes.

Heat loss through ventilation depends directly on windspeed. At an outside temperature of -10°C or below, the air exchange is reduced due to freezing of the cracks and slits. Another result of air exchanges through the greenhouse shell is its effect on relative humidity (RH). When inside air is exchanged with cool and dry outside air, the RH is lowered. These RH differences can be especially important for year-round production. High RH causes plants to grow soft and thin leaves. This is inducive to plant diseases and limits water and nutrient uptake of plants by limiting transpiration. A similar argument can be made for carbon dioxide supplementation. Polyethylene greenhouses require less carbon dioxide supplementation than glass greenhouses to maintain 800-1000 ppm.

Radiation heat losses are the third factor affecting the overall insulation characteristics of a greenhouse. All surfaces produce and receive electromagnetic radiation. The amount of this radiation is governed by its wave length. Radiation given off by the greenhouse canopy, steamlines, benches, etc. are primarily between 5,000 and 20,000 nM and called infrared (IR) or thermal radiation.

IR radiation is either transmitted, absorbed or reflected. Polyethylene transmits a relatively high percentage of long wave radiation (80%), while glass has a low transmissivity or is considered opaque to IR-radiation (4%) by the glazing material. The higher the reflectivity of IR radiation of the glazing material the better the greenhouse effect. However, highly reflective materials are often also reflective to visible radiation. Absorption of the IR-radiation is sometimes considered a good alternative for polyethylene films (IR-films). Although glass has a low transmissivity (4%) it absorbs a great deal of IR-radiation. Certain glass types (Hortiplus) prevent this energy from escaping to the atmosphere by the addition of a low emissivity layer to the outside of the glass. Therefore, a full understanding of the reflectivity, transmissivity and absorptivity (= emissivity) in the short wave (visible light) as well as in the long wave (infrared) region of the spectrum is desirable when selecting a glazing material.

Mechanical Properties

Greenhouses are designed and manufactured according to the Canadian Farm building code (NRCC, 21312, 1983) to withstand structural loads (dead and live) as well as loads which are site-specific such as snowload and windload. The dead

load includes the weight of the structure and all permanent hardware while the live load primarily covers the weight of plants and/or temporary equipment. Snowload is a concern for Ontario growers on a yearly basis. In southern Ontario, design and manufacturing calls for a minimum of 75 kg/m^2 for snowload. Snowstorms can vary in wind direction, wind speed and accumulation rate, type of snow and outside temperature. Therefore, municipal bylaws may vary from the above standard, depending on climatic conditions. All gutter connected greenhouses should have some auxiliary heating lines near the gutter to melt the snow. For glass covered greenhouses it is the design of the greenhouse that has a large influence on snowloading. Gutter connected widespan (>7.5m wide) having high ridges and aluminum glazing bars are usually the most affected during a snowstorm in southern Ontario. Large amounts of snow may accumulate in the gutters and the melting of the snow around the aluminum glazing bars causes the snow to rest directly on the glass. Excessive snowloads usually break the glass but not the structure. However, tempered glass which is often used in areas of high snow accumulation may require a different design load for the structure.

In the case of inflated plastic films the weight of the snow presses the two layers together reducing the insulation value and allowing a quicker melting. However, the high load bearing capacity of polyethylene films has to be considered when designing a greenhouse for a specific region. Snow accumulation can be a concern for twin-walled rigid panels, either glass or plastic, because of the high insulation value. Manufacturers often recommend optimal glazing bar spacings and these should be followed to maintain warranty. With films a proper interlocking extrusion has to be installed. These interlocking (aluminum and/or plastic) are usually manufactured to accommodate certain film thicknesses (e.g. 4 x 150 microns) and this should be considered when changing film thicknesses.

The impact strength is important to withstand hail damage. Fiberglass has been used extensively in the western provinces as an alternative to glass. Most films as well as polycarbonate have an excellent record in terms of hail damage. However, in case of freezing rain, thin layer(s) of ice may be formed on the roof which is then subject to breakage by the wind. These thin razor-like sheets of ice can do substantial damage to greenhouse films, especially the outer layer. Repair is done using special repair tape.

Materials Used

Greenhouses are structures covered with a transparent material in order to grow plants. The growth of the plants are determined by light (intensity and duration), as well as relative humidity (RH), plant temperature and carbon dioxide. Although light transmissivity is important for plant growth, the effect of RH and plant temperature on the overall growth becomes more evident now that more experience has been obtained with the different glazing materials. The RH is determined to a great deal by the air exchange rate of a building, while the plant temperature is affected by the emissivity and absorptivity of the glazing material in the infrared spectrum.

Glass Historically, glass has been the preferred glazing material for greenhouses because of high light transmissivity characteristics and longevity. Transmissivity for 40-year-old glass differs little from that of new glass. The material is made by heating a mixture of sand, limestone and soda ash to 1500°C. The resulting liquid is then poured on a molten tin bath to obtain a prescribed thickness and a flat surface (float glass). The material is then cooled down and cut to size. The standard size in Ontario is 610 x 660 mm with a thickness of either 3 or 4 mm. The light transmissivity is usually between 88 and 90% for perpendicular light, the variation being normally due to impurities in the base materials. A low iron glass (0.04% Fe) will provide maximum light transmissivity (Solatex).

Tin oxide coated glass (Hortiplus) is a form of glass whereby the thermal properties of the greenhouse are improved by having a low emissivity (0.15) compared to that of standard glass (0.90). Optimum energy savings from Hortiplus are achieved on a clear night and a dry surface on the outside of the glass. Reported energy savings are in the area of 15-25% compared to ordinary glass.

Another form of glass, which is useful from a structural strength point of view, is tempered glass. This glass has the optical and thermal properties of ordinary glass but is 4-5 times stronger. It is used often for the two or three bottom rows on the roof of greenhouses of 6.0 m and wider to prevent breakage due to snow loading and/or ice moving from the adjacent house in gutter-connected ranges. A unique feature of tempered glass is that it can be applied on slightly curved rafters. Tempered glass cannot be cut and therefore has to be ordered to size.

Double-layered glass comes in different forms. The most common is "Sedo" glass from Germany. This material is made from two layers of 3 mm thick glass with a space of 9 mm for a total of 15 mm. The sides of the panes are molded and the cavity space is filled with pure carbon dioxide. The material comes in six standard sizes and special glazing bars must be used. Energy savings are in the range of 40-50%. It is not used in North America.

A unique feature of glass is its effect on relative humidity in a greenhouse. The lapping of single glass panes allows condensation, which always forms on the inside of panes to drain towards the outside of the greenhouse and eventually into the gutter. Additional reduction of RH is provided by the naturally high rates of air exchange. Generally, 1-2 air changes per hour occur in a glass greenhouse depending on structural maintenance and windspeed. The application of a bead of silicone on the glass overlap reduces air infiltration considerably but invariably causes dripping inside the greenhouse due to the blockage of the condensate water.

Plastics Increases in fuel prices, the threat of fuel shortages in the long-term, and new developments in plastic technology have prompted re-evaluation of glass as a covering material for greenhouses. Many different plastic materials have been produced in the past few years but they are not all suitable as greenhouse cover. Those used for greenhouse coverings fall into two categories:

a. film plastics, including polyethylene, or copolymer of polyethylene and vinylacetate (EVA), polyvinylchloride, polyester and polyvinylfluoride.
b. rigid plastic panels, including fiberglass reinforced panels (FRP), acrylics and polycarbonate.

Plastic Film

Polyethylene Polyethylene (PE) is the most widely used greenhouse film. It is produced by mixing homopolymers of ethylene with an ultraviolet (UV) inhibitor package. Depending on the inhibitor package the film is sold on the basis of a life expectancy of two or three years for normal exposure. The major North American manufacturers also add vinylacetate to the polyethylene. These films are copolymer films and referred to as an EVA-film. EVA-films are more flexible, stronger at lower temperatures, and have an improved absorptivity of infrared radiation compared to the homopolymer films.

Polyethylene is manufactured through extrusion whereby pressurized air is forced into the polyethylene to form a tubeshaped film with normal widths up to 7.3 m which can be slit to produce a single sheet. Common thicknesses are 100 (4 mil) and 150 (6 mil) microns.

Polyethylene greenhouse film is tough, flexible and relatively inexpensive. It can withstand temperatures as low as -30 to -50°C, but temperatures of 80 to 90°C will cause it to melt. Above 60°C, it loses much of its strength and may stretch markedly. Construction grade polyethylene does not have an UV inhibitor package added and will break down after three to five months due to photo-chemical degradation. All greenhouse films are UV-stabilized. Punctures and/or slits, occasionally caused by flying debris such as ice, are best repaired with black polyethylene tape. Do not use plasticized vinyl tape.

Single-layered polyethylene with its continuous condensation problems is seldom used commercially except for short spring crops such as bedding plants. Instead, air-inflated double-layered polyethylene has become popular in Ontario for year-round production. Triple or quadruple layers have not been used because of low light transmissivity, difficulty of application and the reduced economic benefit of additional layers.

One of the drawbacks of films is the high transmissivity of infrared or thermal radiation in the 5,000 - 20,000 nM wavelength. For an optimal greenhouse effect one requires a high transmissivity for visible light (400-700 nM) and a low transmissivity of infrared radiation. Greenhouse manufacturers have recently started to incorporate IR-absorbers in their formulation to reduce the thermal heat losses. Commercially available IR-films absorb 55 to 85% of the infrared radiation. Savings of 15-20% are obtainable compared with ordinary UV-stabilized film. The compounds presently used as IR absorbers in these films are

non-selective to only IR-wavelength. Light transmissivity for IR films is reduced as compared to ordinary polyethylene films. Future research will provide additional information on strength, breakdown and light transmissivity of these films.

Another aspect which is important in polyethylene greenhouses is water condensation. Polyethylene film is considered hydrophobic and water vapor condensing on the inside of the inner layer will form relatively large droplets. Besides being a nuisance, this reduces light transmissivity considerably (5-10%). The use of a surfactant (e.g. Sunclear) helps to prevent droplet formation by causing water to adhere as a thin film to the polyethylene. The active ingredient of "Sunclear" is not irreversibly bound but merely absorbed onto the film. Condensation on the inside layer will disassociate and dilute the compound until no active sites remain. The rate of condensation determines the rate at which the "Sunclear" will remain active. So far, attempts to incorporate a surfactant into the film formulation have not proven to be more successful than hand-applied surfactants.

Double polyethylene film is inflated by air to a pressure of about 5-8 mm water column. Outside air should be used for this to prevent excessive condensation between the two layers (Figure 2). EVA-films have (in contrast to homopolymers) a low resistance to water vapor and consequently water vapor may enter between the two layers over time, resulting in reduced light transmissivity and possibly algae growth.

Dust accumulation on polyethylene films are not uncommon and regular washing with a mild soap or detergent is recommended.

Polyvinyl Chloride (PVC) Similar to glass, polyvinyls have a high degree of solar transmittance and UV-treated PVC has better resistance to weathering than polyethylene and may last up to five years. The main disadvantage is the narrow widths (1.25 to 2.20 m) available. Heat sealing to obtain wider spans to accommodate glazing bars can overcome this problem. In addition, the electrostatic charge usually associated with vinyls causes dust particles to adhere to the film. PVC films are used widely in Japan but its application in other parts of the world has not been extensive. Its cost and poor low temperature impact resistance are major drawbacks.

Rigid PVC twin-wall panels (e.g. Thermolux) are used only on an experimental basis (Agriculture Canada Research Station, Harrow, Ontario). In Europe it is marketed under the name of Maxolux or Rodica. Its weatherability record and hail impact resistance remain a concern to growers.

Polyvinyl Fluoride (PVF) PVF has been used for years as a greenhouse film. It has excellent weatherability (10 years) and high transmissivity to solar radiation. The material has an excellent impact strength (hail) but poor tear resistance. It comes in widths of 1.20 - 1.80 m. It is good for use as an inside layer in a greenhouse or as a dividing wall and is marketed under the name Tedlar.

Polyester This material is widely used in the textile industry and regarded by some as having great potential for the plastic greenhouse industry. The material has a light transmissivity comparable to glass (Table 2), is very strong, although it

has poor tear resistance, and can last up to 15 years. At the present time polyester and polyvinyl films are produced using a calendering machine resulting in a film width of 1.5 m and is consequently impractical for greenhouse use. The price of polyester film is about three to four times higher than that of polyethylene. Commercial products are Melinex OW, Melinex 071, Mylar or Llumar. The difference between Melinex OW and Melinex 071 is that the latter has antifogging properties and a higher light transmissivity. Melinex 071 is therefore an excellent material as a second or third layer in a greenhouse for both energy conservation purposes and/or dehumidification.

Rigid Panels

Fiberglass-reinforced panels These panels consist of glass-fiber reinforced polyester (FRP). The panels have been very popular in areas of high light intensity such as the southern U.S.A. Modified panels, containing a 15% acrylic additive and polyvinyl fluoride coatings to prevent weathering, have increased the suitability of the basic polyester formulations. Older types of fiberglass resulted in considerable problems because of delamination and discoloration.

Fiberglass is available in both corrugated and flat panels in weights ranging from 1.2 to 1.5 kg/m^2, in widths up to 1.2 m, and in lengths up to 9 m. Fiberglass materials are guaranteed against only natural mechanical breakdown for up to 15 years, depending on the quality of the product. Corrugated panels are preferred for roofing because of their greater strength. Corrugations in the material increase heat loss by about 10 to 15% due to the increased exposed area. However, they do not require special glazing bars and are fastened directly on rafters and purlins. Corrugated panels are not popular in the colder areas such as Ontario, but are more widely used in British Columbia. Common names are Lascolite, Filon, Denverlight and Excelite.

Acrylic Panels A single-layered material sold under the trade name Plexiglass has been marketed for more than 50 years. Its high light transmission, excellent flexibility, strength and weatherability compare favorably with glass. High cost has hindered its adoption as a greenhouse covering. Another common name is USS acrysteel (3 mm).

A double-layered material is available in 6, 8, 10, 16, or 32 mm thickness. A commonly used example, made in Ontario, Canada is Acrylite SDP 16. The rigid panels are 16 mm thick and 1.21 m wide (Figure 7). The ribs which separate the two parallel sheets are about 16 mm apart. It should not be applied in a curved manner. Special glazing bars are required to allow for the contraction and expansion (7 x 10^{-5} cm/cm/°C) for the 16 mm material. Energy savings with this material are expected to be 40-50% compared to single glass houses but high snow loads can be expected in widespan houses if no provisions are made for rapid snow removal. The relatively high costs and the need for special glazing bars prevent many growers from using this material. Thinner materials (8 to 10 mm thickness) are being tested on gothic or arch shaped houses. The RH in the

winter can be expected to be higher in such a house due to lower rate of air infiltration and less condensation on the double-skinned sheet. Good light transmissivity and durability are positive characteristics in addition to the energy savings. Most newly constructed greenhouses use Acrylite SDP-16 as glazing material for the sidewalls (Figure 4). Commercial names for double-skinned products are Acrylite SDP, Lucite, Exolite and/or AcryCel.

Polycarbonate Panels These panels are available in double-skinned sheets. "Qualex" and "SDP-polycarbonate" are examples. Qualex, a relatively new material on the market, is similar in construction to SDP sheets but is thinner and more flexible (Figure 7). The material comes in either 4 or 6 mm thickness. Qualex is less expensive than SDP-16 acrylite.

SDP polycarbonate sheets are similar in physical dimensions to those of SDP-acrylite but are stronger and have lower light transmissivity. The linear expansion of the material requires a glazing bar similar to that for acrylics. Its price is approximately 25% higher than SDP-acrylite. Polycarbonates are sensitive to UV-degradation unless coated with an acrylic. Common names are Lexan, Tuffak twinwall, Qualex, PolyCel, Polygal and Cyrolon SDP.

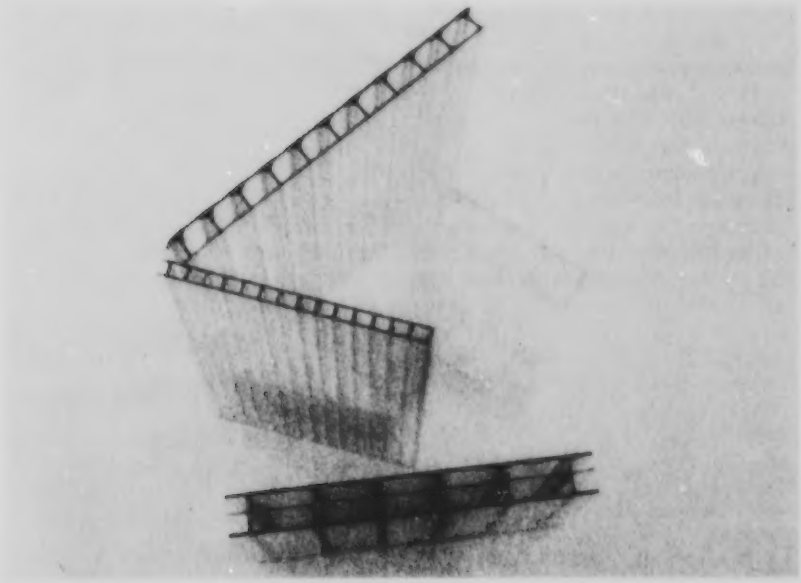


Figure 7. A cross-sectional view of some double- and triple-layered structured sheets.

Coroplast This material comes only as a double-skinned structured sheet, similar to the SDP materials (Figure 7). It is made of polypropylene and 5 mm thick. Fastening to structure can be done by screws or nails. Due to low light transmissivity, it is only being used in corridors. Life expectancy is about 5 years.

Cost and life expectancy of several glazing materials

The approximate cost and life expectancy for several glazing materials is given in Table 4.

Table 4. Cost and life expectancy of several glazing materials (1985 prices)

	Cost ($/m^2)	Life expectancy (years)
Glass, 4 mm	8.50	30+
Double polyethylene, 150 micron UV-treated, 3 yr.	2.00	2-3
Double polyethylene, 150 micron UV-3 year, IR absorber	3.50	2-3
Acrylic, SDP, 16 mm	30	15+
Polycarbonate, SDP, 16 mm	38	10+
Polycarbonate, Qualex, 6 mm	12	5+
Fiberglass, Filon SP-15, 1.5 kg/m^2	9	15 (only on mechanical)

Consideration must also be given to other costs such as building the structure and glazing. An estimate of these items is presented in "Construction Costs."

Construction Costs

There are many different types of greenhouse construction as well as different options possible within the structure. A summary of the most common items is provided in Table 5. Prices provided by different greenhouse suppliers are based on a 1000 m^2 structure.

Table 5. Estimated greenhouse construction costs (1990) for a 1000 m² gutter-connected range

Common items	Galvanized or aluminum truss + glass	Galvanized truss + double polyethylene
	$/m²	$/m²
Structure (glazing and vents included)	50-90	35-50
Construction cost	20	10
SDP for end and sidewalls; extra	12	8
Heating — boiler (40 hp steam)	18	18
— heating pipes and installation	23	18
H.A.F. (Horizontal Air Flow)	2	2
Thermal curtain — 50% shade	18	18
— 100% shade (blackout)	25	25
Supplemental lighting		
HPS @ 40 W/m² installed	25-30	25-30
Watering system — drip (low volume)	6.50	6.50
— spaghetti	4.50	4.50
— overhead	3	3
— high pressure mist/fog	8	8
Benching — stationary (galv. metal)	20	20
— movable (galv. metal)	23	23
— Ebb and Flow	50	50
Electricity — service and installation	6	6
— new service — add	10	10
Equipment — generator — cooler	14	14
— environmental computer	15	15

Other Costs

1. Site clearing and levelling: $5,000.
2. Boiler room — packing room: $20,000 (7 to 8% of greenhouse area @ $270/m²).
3. Hot water heating is about $1 per m² more than steam.
4. Land value is not taken into consideration.
5. A freestanding double polyethylene greenhouse (29.5 x 8 m) with galvanized truss and 0.9 m sidewall would have a material cost for structure of $30/m². Other costs as above for double poly gutter-connected.

Insurance

In addition to the original capital cost, the grower should be aware of the insurance status of each type of greenhouse. Greenhouse insurance is comprised of three components: glazing materials, structure and fixed equipment such as fans and lights, and the crop. According to the major greenhouse insurance company, the following policy was in effect as of 1985:

- Glazing materials such as glass, fiberglass and SDP are insurable at replacement costs. Polyethylene glazing is not insurable.
- Structure and fixed equipment of greenhouses can be insured at replacement costs. A minimum coverage of $45 per m^2 is needed for polyhouses and $90 per m^2 for glass.
- The value of the crop can be insured provided the covering is either glass, double polyethylene, SDP or fiberglass. No crop insurance is available for single-layered polyethylene greenhouses.

3. GREENHOUSE ENVIRONMENT

Heating

Greenhouses are usually poorly insulated buildings from an engineering viewpoint. Large amounts of heat are required especially during the winter to maintain temperatures optimal for plant growth. To provide a uniform temperature distribution throughout the greenhouse, the heating system needs to be carefully planned and designed.

Heating requirements for a greenhouse range can be calculated on a yearly as well as on an hourly basis. Inside and outside temperatures, the type of glazing material and surface area of the greenhouse should be known. Sample calculations for different types of greenhouses are presented in Ontario Ministry of Agriculture and Food publication 65, *Energy Conservation in Ontario Greenhouses*. The standard recommendations for a 35°C temperature differential are 350 W/m^2 for a glass greenhouse and 270 W/m^2 for a double polyethylene greenhouse. These recommendations are valid for large greenhouses (4000 m^2 and more) and most areas in southern Ontario. If thermal curtains are installed, 25 to 35% can be subtracted from these figures.

The type of heating system required depends on crops to be grown and glazing material. There are three distinct ways to heat a greenhouse.

Central Heating System Heat is provided in the form of steam or hot water from a centrally located boiler. Packaged boilers with forced convection (firetube) are the most common. To provide flexibility, the boiler is usually fitted with combination burners which can burn both natural gas and oil. Water is the heat transfer medium and is circulated through heating lines either as hot water or steam.

In most older greenhouses, heating lines are located near roof trusses where they are close to the area of greatest heat loss and do not interfere with cultural operations. In addition, perimeter heating lines are installed to offset wall losses.

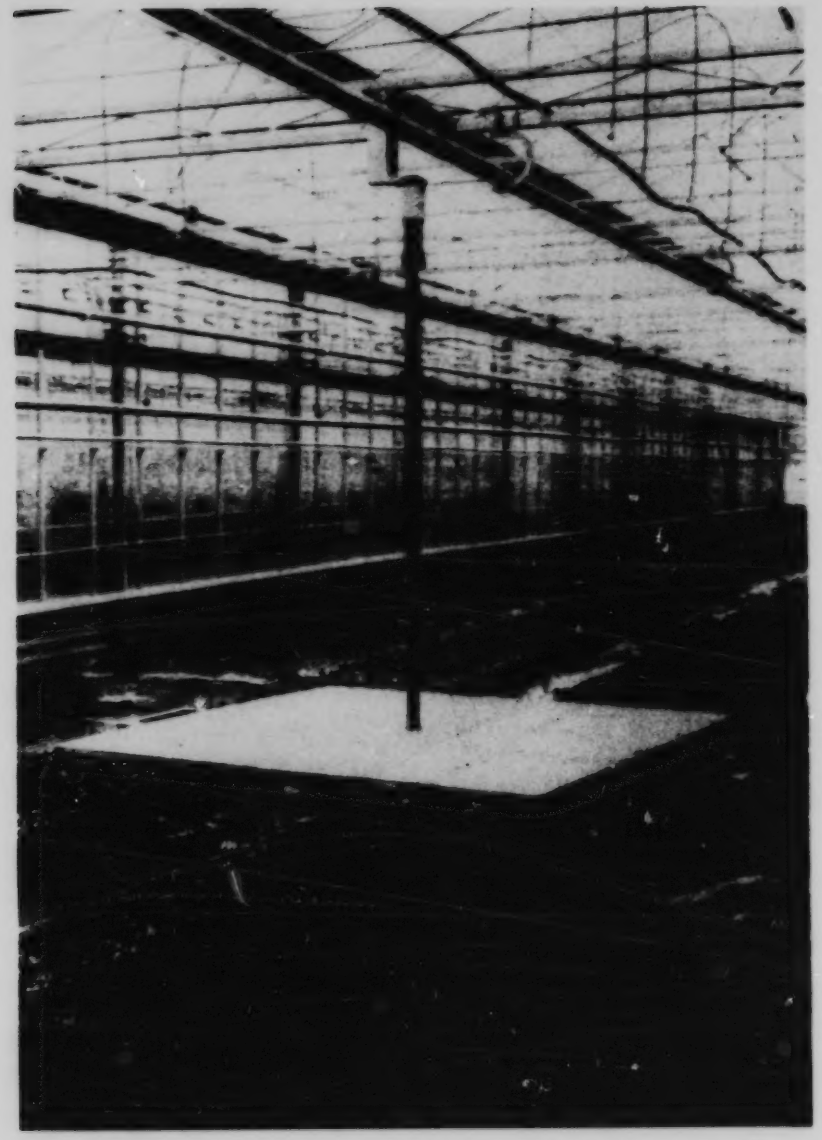


Figure 8. An example of a heating line which is also used as a monorail.

Low pressure steam is the predominant system used by growers. However, plants in close proximity to the pipes usually cannot withstand the extreme amounts of heat from the pipes. Some growers with greenhouse operations used for year-round production have installed hot water systems. Hot water boilers are "closed" systems requiring less chemicals for water treatment compared to steam. Temperatures up to 110 to 120°C can be obtained with pressurized hot water and the heating pipes may be located anywhere. Because warm air rises, heating lines are located near ground level especially with cut flowers or bench crops. This is often referred to as crop heat. In special cases, heating lines can be used to support movable benches or as guides for a monorail system (Figure 8). Where potted plants are grown on the ground, or where a crop requires a higher root temperature compared to air temperature, heating lines are buried in the ground. In most cases, polybutylene or polyethylene tubes are used for heat transport in soil heating systems. The top or side heating system provides the remainder of the heating requirements. With hot water heating not only the air or soil temperature can be controlled but also the water temperature. In areas of high snow incidence, growers may consider a combination of steam and hot water. The steam heating system is only to be used if a sudden demand is required (e.g. snow, opening of energy curtain in the morning or steam sterilization). The grower will then install steamboilers with a converter set (steam to hot water heat exchanger) for the hot water system. As an option some hot water boilers can be equipped to produce steam for soil sterilization.

Although the combustion efficiency of gas or oil fired boilers can range between 80 to 85%, the net amount of heat in the greenhouse is usually about 65 to 75% of the total heat input, with hot water heating systems generally being more efficient than steam heating. Uniformity of heat distribution and versatility are the main advantages of a central heating system.

Forced-air Heating Gas-fired unit heaters (Figure 9), are often used by growers of seasonal crops, especially those who are using double polyethylene greenhouses. Although the combustion efficiency of these unit heaters (65 to 75%) may be lower than that of boilers, this system can be installed very economically. One major drawback is the lack of uniformity in heat distribution. Fans can help to reduce this problem significantly. Uniformity in heat distribution is even more important to the year-round growers. Many small units are preferred over one or two big units. In gutter-connected houses the units should be located at alternating ends of the greenhouse and connected to a fan-jet system.

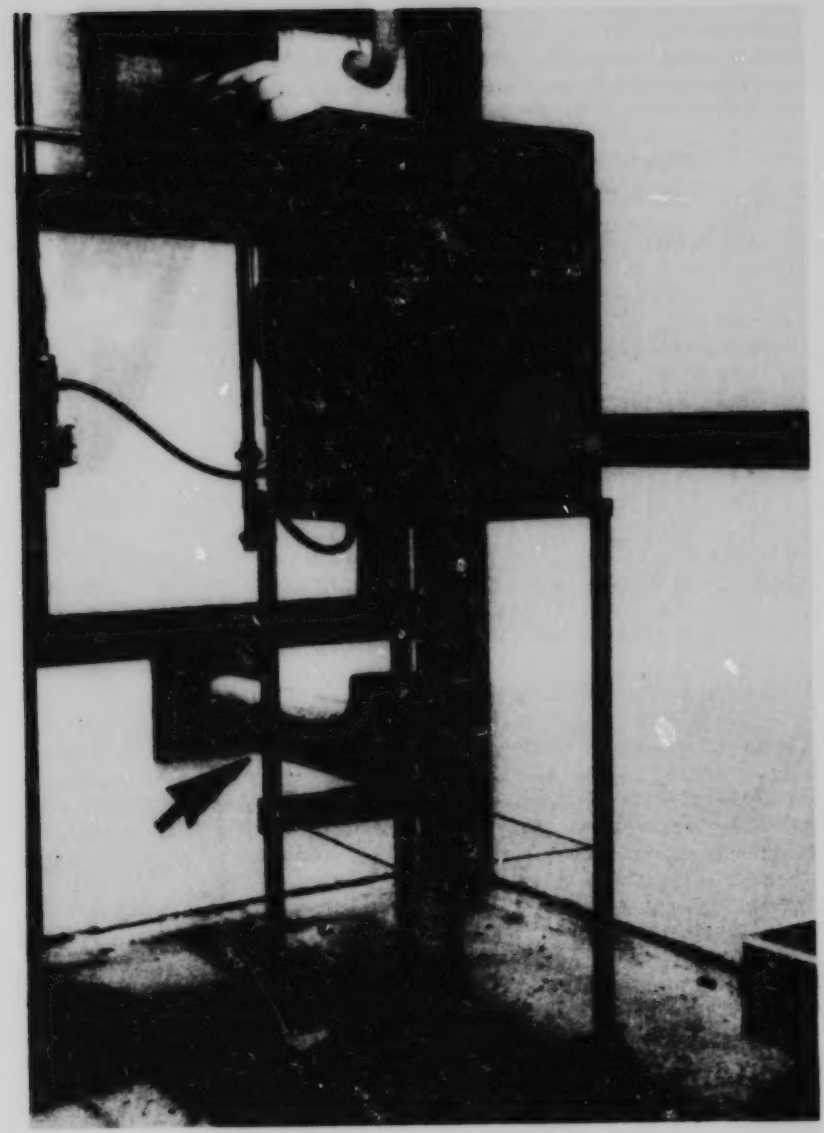


Figure 9. An atmospheric type of gas-fired unit heater. Note the supply of fresh air to heater.

A second problem is the potential for air pollution from impurities or if incomplete combustion gases are allowed to enter the greenhouse environment. Provision should be made for fresh air to reach the burners especially in airtight houses. An opening of 10 cm^2 is needed for every 1000 W burner capacity. Newer sealed combustion units have provisions for fresh air at time of burning, and are more energy efficient. Flue gases must always be exhausted outside the greenhouse. A regular check should be made for any cracks in the heat exchanger part as flue gases and unburned fuel may be drawn into the greenhouse by the air circulator.

Infrared Heating "Low intensity infrared heating" for greenhouses is a recent development. It is based on the principle that objects are primarily warmed by radiation emitted from a hot pipe rather than convective heat transfer. A black steel tube positioned in the peak of the greenhouse with an outside diameter of 10 cm is heated by one of several 17,600 W gas-fired burners as the flue gases are being sucked through the pipe by a vacuum pump, positioned at the end of the pipe. Heat radiating from the pipe is directed downwards by reflectors heating any object in its path. The flue gases from the burners are exhausted outside the greenhouse after it is allowed to reach its dewpoint. These features make the system an extremely efficient converter of fuel into sensible heat.

Uniformity of temperature within the greenhouse is difficult to obtain and careful consideration should be given to the layout of the IR system especially for freestanding houses. Crops with a large, tall canopy (roses, cucumbers) and a high energy demand have shown temperature stratification and unevenness in maturity. Burners in existing low intensity infrared heating systems (Co Ray Vac) can only utilize natural gas and propane.

Cooling

During periods of bright sunlight, air temperatures in a greenhouse will rise above outdoor ambient due to the net heat influx and the reduced air movement. Incoming radiation during summer months of approximately 17,000 kJ/m^2 per day is the primary cause of elevated temperatures. Temperatures of plant and greenhouse air must be lowered; this is accomplished by a combination of transpiration and ventilation.

Under optimal conditions, plant temperature can be regulated by the rate of transpiration. A full-grown crop can transpire up to 5 L/m^2 of water per day. This rate of evaporation provides about 12,500 kJ/m^2 of cooling per day. The remainder of the heat load must be removed, or excessively high temperatures will occur thus reducing natural transpiration and plant growth.

Ventilation, the conventional method of lowering the air temperature, is accomplished by drawing cooler outside air into the greenhouse. Different methods of ventilation are available and they vary primarily in cooling capacity. When considering cooling for a greenhouse range it is important to appraise the requirements of the different seasons. In attempts to build inexpensively, growers often install a ventilation capacity inadequate for extreme summer conditions. Ventilation must be considered a year-round process. During the winter a reduced

capacity is needed to avoid excessive chilling. Winter ventilation is often used to reduce relative humidity.

There are three distinct systems whereby cool air is mixed with greenhouse air to reduce the temperature. Each system has its own characteristics, and choice of installation depends on the final purpose.

Convective Cooling by Roof and/or Side Ventilators

Natural ventilation is the oldest form of cooling. No mechanical means is required to move the air other than the natural forces such as windspeed and temperature difference between inside and outside of the greenhouse. Both mechanisms can make significant contributions to the air exchange rate and normally one cannot be separated from the other. The air exchange rate also depends on ventilator area, the extent of opening, and wind direction. The most common situation is that the vents cover 25-30% of the roof area, with vents on both sides of the ridges (Figure 10). In areas where there is a prevailing wind, the top ventilator is only installed on the leeside of the peak to reduce construction costs. Some growers combine the systems using a roof ventilation, during periods when small amounts of air are needed for cooling (fall, winter and spring) or for reducing relative humidity, and a forced ventilation system during the summer. Control of the roof vents should be correlated so that the leeward side opens first and then the windward side. The vents on either side of the peak are usually connected to a shaft by means of a rack and pinion system. A reversible (3 phase) motor is connected to the shaft for the opening or closing. Some freestanding greenhouses are equipped with side and ridge vents to provide cooling by convection only.

Figure 10. A continuous double ridge vent system.

Roof top ventilators have been the standard method of cooling on roofs with a rigid peak such as glass or SDP acrylic greenhouses. Occasionally one may find roof vents on gothic shaped polyethylene greenhouses.

Forced Cooling System Using Electrical Exhaust Fans and Inlet Vents

This system is used primarily for cooling during periods of high temperatures especially in houses which do not have roof vents (polyethylene houses). Ventilation is provided by electrical exhaust fans which are set in the side of the end wall, drawing fresh air into the house from open ventilators on the opposite side or end wall. The fans as well as the vents are located 0.5 to 1.5 m above the ground, depending on the crops to be grown. Large-capacity, slow-speed, belt-driven propeller fans are most frequently used (Figure 11). They are quiet and move large volumes of air at a slow speed. Smaller fans (less than 60 cm diameter) can be obtained as direct drive fans and are available with single or variable speed motors. Direct drive fans are subject to vibration and end thrust forces and usually require more maintenance. Manufacturers offer a complete range of fans in diameters ranging from 0.6 to 1.4 m in 0.15 m increments. The capacity of a fan to move air is referred to as its air delivery rating, usually stated in cubic metres per hour. For greenhouse fans which run an appreciable number of hours it is wise to compare the ventilation efficiency coefficient of fans (the ratio of air delivery per unit of energy consumed).

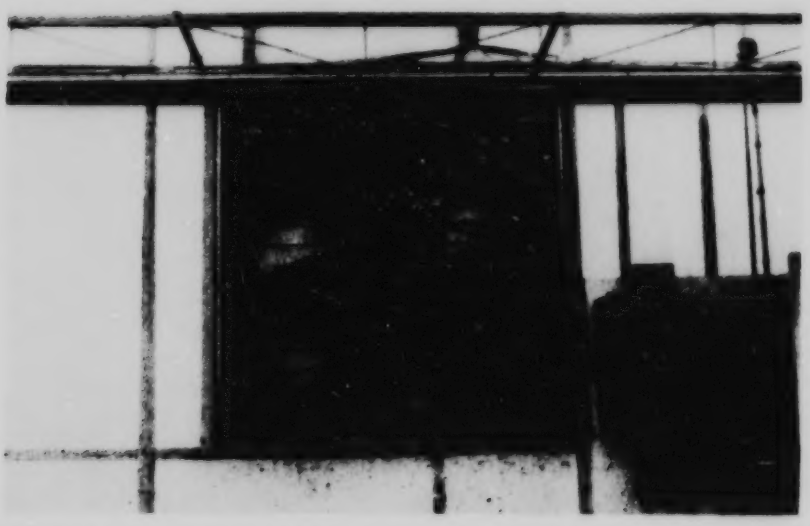


Figure 11. A louvered belt-driven exhaust fan commonly used for greenhouse ventilation.

Shutters which are positioned on the downstream side of the fan are usually pressure operated and do not require a motor. Ordinarily, the recommended ventilation capacity is about one air change per minute or about 2.5 m^3 of air per m^2 of greenhouse floor per minute. Where two or more fans are required, they should be placed not more than 8 m apart for uniform air movement through the greenhouse. If possible, they should be located in an end wall, drawing the air down the long axis of the greenhouse or along the benches.

Since air warms as it passes through the greenhouse, the distance from intake to the fan should not be too great; preferred distance is less than 65 m. Distances larger than 65 m will cause warmer and cooler spots in the greenhouse. Vent openings are important because these influence the wind velocity entering the greenhouse. High wind velocity is especially important during cool winter weather, to prevent cold pockets near the vents.

With certain crops, notably those requiring cooler temperatures during the summer, it may be beneficial to have an evaporative cooling system installed at the vent opening. The air is drawn through continuously wet fibrous pads (Figure 12). This system is often referred to as "fan and pad cooling."

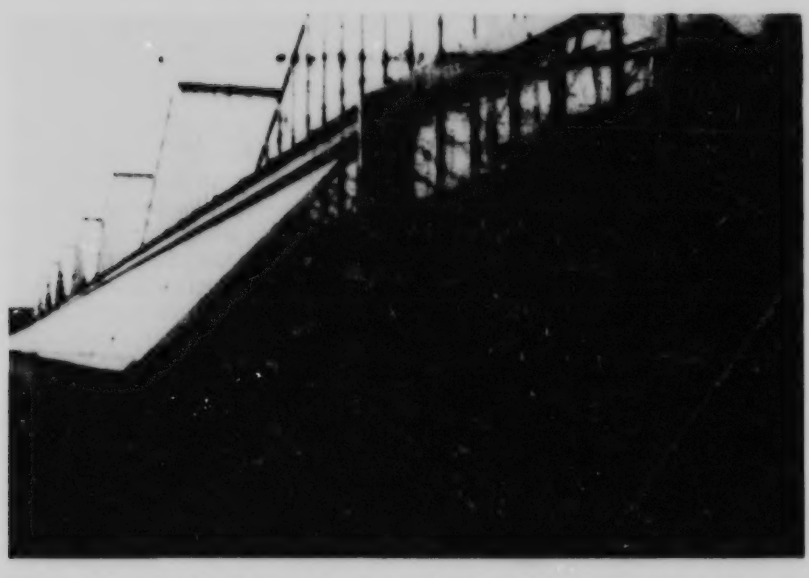


Figure 12. The "pad" part of a fan and pad cooling system. Note the water supply tube with the nozzles to keep the pad moist.

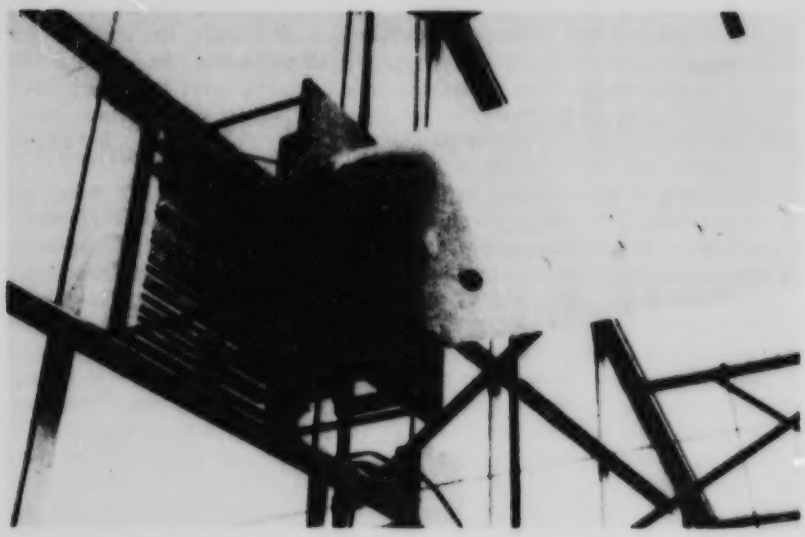


Figure 13. A forced-air convection system using a perforated polyethylene tube for air circulation and first-stage cooling.

Fan-jet System

This system consists of a tube-pressurizing fan which is a perforated polyethylene tube and an air inlet shutter (Figure 13). The fan capacity should be about 0.4 to 0.6 m^3 of air per square metre of greenhouse floor area per minute. The air inlet device consists of a spring-loaded shutter fastened to the exterior of the house and a tube housing fastened to the interior. The shutter device, which opens outward, may be motorized for automatic operation under thermostat and/or humidistat control. The shutters are always installed at the gable ends about gutter level. Usually the shutters are opened at the first stage of cooling. A perforated polyethylene sleeve, 45 cm or more in diameter, is fitted to the circular flange of the tube housing and suspended by wire the length of the house. The opposite end of the tube is tied with twine, and connected to a wire over a pulley with a weight to allow for expansion and contraction of the tube.

Fans usually run 24 hours a day to provide air circulation within the greenhouse. The location of the holes in the poly tube determines the direction of the airflow. Air holes may have to be altered depending on the directional flow requirements. Airflow should be directed just below the gutter rather than against the greenhouse roof to prevent excess heat losses during the winter. In gutter-connected houses, fans may be positioned at alternating ends of adjacent houses

to provide better air circulation and temperature distribution. To obtain effective cooling from the fan-jet system in very tight houses (PE-houses) it may be required to install an exhaust fan to provide an outlet for the air rather than building up a static pressure within a greenhouse without any volume of air moving.

Alternate Cooling Systems

Another method of cooling a greenhouse is by reducing the amount of incoming solar radiation. Some porous thermal curtains are excellent for reducing radiation influx. The main advantage of using a thermal curtain is the possibility of quick removal during low light periods (mornings and evenings). Still another way of reducing incoming radiation is by means of a shading compound sprayed on the glazing material. Both methods are very effective in reducing the greenhouse air and plant temperature.

High pressure misting systems (4000 to 8000 kPa) are becoming popular in North America. These are activated by time clocks and/or photostats and produce an extremely fine mist. The evaporation of fine water particles cools the surrounding air but should not create a condensation layer on the foliage. The system will therefore also increase the relative humidity, and can be used for planting young crops requiring both high light intensities and high relative humidities.

Other techniques for cooling, such as the use of wooden laths or the continuous colored water flow technique on the greenhouse roof, do not appear to have any commercial application.

Air Circulation

The use of energy curtains has made it necessary to look at alternatives to the conventional fan-jet system for air circulation. The use of horizontal air flow (HAF) is an example and is less costly from an energy point of view. The fans used are usually small (30-45 cm diameter) and require little energy (25-50 W) to obtain a linear air velocity of about 10-12 m. min. An energy efficient permanent split-capacitor (PSC) motor works well. The fans are to be located so that air will move along the longitudinal axis of the house. The distance is usually 5 m from the end wall and then every 12-15 m for each bay (5-8.0 m wide) at a height of 2.5-3.0 m. Adjacent houses should have the air flowing in the opposite direction. Additional information is given in the Connecticut Cooperative Extension Service Greenhouse Newsletter #125, 1985, *Horizontal Air Flow*.

Relative Humidity

The lack of reliable humidity sensors has been the primary reason that the control of the relative humidity (RH) has been neglected in greenhouses. The introduction of computers in combination with the use of wet and dry bulb sensors has made it less complicated to monitor and ultimately control the RH in a greenhouse. During the last decade a better understanding of the effect of RH and its interaction with other environmental factors on crop production has been

obtained. Why is the RH so important in greenhouses? Before answering this question one has to understand first what RH is and how RH is interrelated with the air temperature.

Relative humidity is the ratio of actual pressure of water vapor in the air to the pressure if the air was saturated with moisture at the same temperature. As there is a unique relationship between the water vapor pressure and the water content in the air, the following definition can also be used: Relative humidity is the ratio of the actual amount of water vapor present in a given volume of air (= absolute humidity) and the maximum amount which can be held in that volume of air at a given temperature. The RH is given as a percentage. It will vary between 50 and 100% in most greenhouses. The actual water vapor content (absolute humidity) in air at 18°C and various RH is presented in Table 6.

Table 6. Water content of air at 18°C for various relative humidities

Relative Humidity %	Water Content (g/m^3)
100	15.7
80	12.6
60	9.4
30	4.7

The amount of water vapor which air can contain is strongly correlated with temperature, as illustrated in Table 7, almost doubling for each 10°C increase in temperature.

Table 7. Effect of temperature on the saturated water content of air

Temperature °C	Water Content (g/m^3)
-20	1.1
-10	2.4
0	4.9
10	9.5
20	17.8
30	31.8

If greenhouse air is either heated or cooled without changing the actual amount of moisture present, the RH will decrease or increase respectively. For most greenhouse conditions, a rule of thumb is that for each degree Celsius increase in temperature the RH will drop about 4-6%; the inverse is also correct. These RH changes would occur regularly in situations where different day and nighttime temperature regimes are established. For instance, many growers will increase the temperature at sunrise by about 3°C and thus lower the RH by 12-18% and induce

an increased transpiration rate. In the evening the drop in temperature will cause an increase in RH and some ventilation may be necessary.

When moist air reaches its saturation point, condensation will occur on cooler surfaces within the greenhouse. During daytime, leaves are usually warmer than the surrounding air but at night the leaf temperature may drop 1 to 2°C below ambient air temperature. If the RH is near 95%, condensation may easily take place on leaf surfaces. The sporulation of fungi or bacteria is enhanced by the presence of free water (Botrytis) or merely by a high RH for a prolonged period (mildew).

Besides the direct effects of temperature on RH, there are other processes which have effects on the RH in the greenhouse. One of these processes is the evaporation of the vegetated land surface, of which the transpiration from the plants is more important than the evaporation from the soil. Transpiration is important for the cooling of the plant and its surrounding air environment, as heat is needed to transfer water from the liquid to the vapor state. The rate of transpiration is highly dependent on the RH in the air. A lower RH will create a higher water vapor differential between the plant and the air and thus a higher potential transpiration rate. The same holds true for the soil.

The amount of water generated by evapotranspiration from a full crop of cucumbers, tomatoes, chrysanthemums and roses is considerable. Under optimal conditions, it is estimated to be up to 5 litres of water per square metre of greenhouse per 24 hours for a crop with a high leaf surface area index. Optimal conditions are defined as a situation where there is an actively growing crop with sufficient visible radiation, sufficient moisture available to the plant, an RH near 60 to 70% and a temperature of about 20 to 25°C. The transpiration rate is highest during daylight periods, although the amount at night can be appreciable (5 to 20%). During rooting, the objective is to maintain a high RH with similar air and leaf temperatures in order to reduce the moisture losses of the cuttings or seedlings.

The RH also plays an important role on the morphology of the plant such as size and thickness of leaves, stems and fruits. Cell enlargement is caused by the active pressure within young cells. For turgid cells the cell pressure will be equal to cell wall pressure. This cell pressure will be higher when the RH is high and consequently lead to large cells and thin cell walls. In practice it means that a soft crop with a poor keeping quality is grown. The proper level of RH depends on the type of crop but also on the time of the day. Another example may be the finishing period of potted plants. These plants are usually hardened off by reducing the RH in the greenhouse to obtain a plant which can withstand shipping and the home environment better.

For tomatoes it is important that the RH is at 70-75% for the proper release of the pollen from the anthers onto the stigma.

The natural exchange of air with the outside environment, especially during the winter, generally will have a lowering effect on the RH as cool air with a low moisture content is exchanged by warm moist air (see Tables 6 and 7). The rate of air exchange depends on the air tightness of the greenhouse and the exposure to the wind.

The intricate combination of the above-mentioned factors affecting the RH (temperature, evapotranspiration and air exchange) as well as condensation can be best explained by example.

Assume winter conditions without any forced ventilation, a greenhouse temperature of 18°C, and RH of 60% and a full-grown crop present. Assume further, an evapotranspiration rate of 1 L of water per square metre of greenhouse area per 24 hours (one fifth of summer conditions) of which 80% occurs during the day (12 hr). This means that the plants will produce about 66 g of water per hour per square metre. Each square metre of greenhouse area contains about 4 m^3 of air. This means that the absolute humidity will increase by 16.5 $g/m^3/h$ if the transpiration rate remains constant. Moreover, if greenhouse air (60% RH and 18°C, Table 6) contains 9.4 g/m^3, then the theoretical absolute humidity of air would be 25.9 g/m^3, while the saturation point at 18°C is 15.4 g/m^3. This would mean the air would be over-saturated, unless moist air is exchanged with cool (drier) air or condensation has taken place in the meantime.

For single-layered glasshouses, one or two air exchanges per hour are normal and for double-skinned greenhouses (double polyethylene or double acrylic) 0.3 to 1.0 air exchanges per hour are normal. For this example, one air exchange per hour, outside temperature at 0°C and 50% RH will be used. The absolute humidity is then about 2.4 g/m^3 for the outside air (Table 7). Therefore, the absolute humidity in the greenhouse would be $(25.9 + 2.4)/2 = 14.2$ g/m^3 or about 95% RH. If there is any less air exchange, then RH would be 100%, and if there is a higher air exchange, a lower value may be expected, assuming no condensation takes place.

Condensation on the inside of the greenhouse can take a significant amount of water vapor out of the air. The rate of condensation depends on many factors, for example, RH inside the greenhouse, temperature of the glazing material facing the inside of the greenhouse, and air movement within a house. In this respect it is important to note that the RH in single-glazed greenhouses will usually be lower than in double-glazed materials because the surface temperature of a single-layered glazing material will be lower than the inside sheet of a double-layered material.

From the above calculations, it was shown that the RH in a greenhouse can easily reach 90 to 100% due to transpiration, even though some water vapor is lost through natural air exchanges and condensation. Optimal values for RH are 70 to 80% for most crops. This level allows for adequate transpiration and related plant growth processes, and is also conducive to lower incidence of plant diseases. In greenhouses with double-skinned glazing materials, high RH's are prevalent during the winter months. The normal procedure for the removal of excess moisture in greenhouses takes place by ventilation, but heating costs are increased. Other methods such as dehumidifiers or heat pumps are being evaluated, but appear expensive.

Excessively low RH may occur when large amounts of dry air are allowed to enter the greenhouse, such as on a bright sunny day during the early part of the year. During such periods the cooling cycle should be monitored closely. Too much ventilation reduces the RH too rapidly and may result in burning the tender

Figure 14. Carbon dioxide controller for maintaining CO_2 levels.

foliage. Misting systems for maintaining a high RH can be installed to prevent damage to specific crops by low RH.

During the summer, when forced ventilation is needed, a high RH is not often a problem during the daytime, unless a fan and pad system has been installed for cooling. During the nighttime, ventilation and/or heating is often required due to the decreasing temperatures in the greenhouses and the chance that the dew point may be reached.

Carbon Dioxide

During the process of photosynthesis, plants absorb carbon dioxide (CO_2) from the air to produce carbohydrates necessary for plant growth. This process takes place only when there is sufficient visible radiation. As a consequence of plant uptake, CO_2 levels in the greenhouse could drop below ambient levels, especially during periods when little air is exchanged with the outside. The ambient CO_2 level in outside air is about 340 ppm on a volume basis and these levels may be reduced to 150 to 200 ppm affecting dry matter production (10-20% reduction compared to ambient levels). This reduction does not only take place in "no ventilation" situations but also when the ventilation is running. Supplementation during ventilation may be beneficial and/or economical, but must be considered on an individual basis. Adding CO_2 up to ambient levels (340 ppm) during spring and fall (moderate ventilation) should be considered. Research has shown that plant growth is improved (15-20%) in greenhouses when CO_2 levels are increased

to about 800-1300 ppm during the daytime. It should be noted that the level of supplementation also depends on the air movement within the greenhouse. In general it may be stated that the optimal CO_2 level is lower (1000 ppm) with increased air movement. In Ontario, most greenhouse growers with year-round operations introduce supplemental carbon dioxide into their greenhouses and are using carbon dioxide controllers (Figure 14) to maintain certain setpoints. Some controllers have a dual setpoint, namely one for supplementation during set hours and one to maintain a minimum level at all times.

There are different methods of adding CO_2 to the greenhouse. The most common practice has been through the combustion of fuels such as natural gas, propane, or low sulphur containing kerosene. These fuels are burned in special units which are positioned in appropriate locations in the greenhouse. The additional heat provided with this technique may or may not be advantageous depending on the season.

Liquid carbon dioxide has become more popular, even though normally it is more expensive for smaller operations. Better control of CO_2 levels, purity of the material, lack of heat production and an opportunity to supply it within a plant canopy are the main advantages.

The rate of carbon dioxide supplementation is highly dependent on the rate of infiltration of outside air into the greenhouse. Burner capacity or the rate of liquid carbon dioxide supplementation for different greenhouse types is listed in the Ontario Ministry of Agriculture and Food Factsheet, *Carbon Dioxide in Greenhouses,* Agdex 290/27. This Factsheet also deals with such aspects as distribution, costs and dangers of incomplete combustion.

Light and Supplemental Lighting

Light is one of the most important factors for greenhouse production. Light provides the energy to convert carbon dioxide and water into carbohydrates within plants (photosynthesis). These carbohydrates are the building blocks for plant life and in general for our food chain. Only about 10% of the light energy which we receive from the sun is converted into chemical energy to be used for respiration and growth. The total amount of radiant energy received from the sun at a horizontal surface is given in Table 8 for southern Ontario.

Table 8. Global radiation (five-year averaged values) measured at Vineland Station

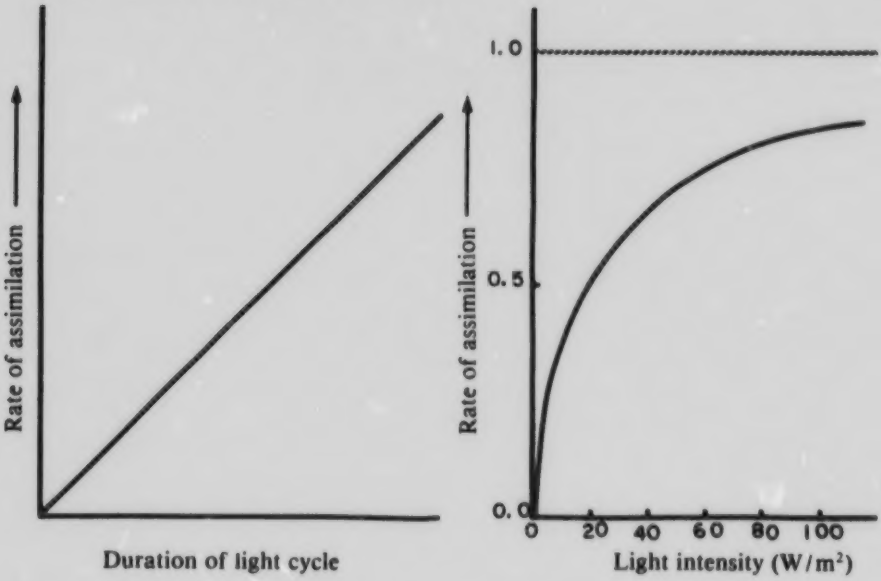
	Average daily incoming radiation [J/cm²/day] (1)	Average day-length [hrs] (2)	Average photosynthesis active radiation (PAR) in greenhouse [W/m²] (3)
January	427	9.3	38.2
February	804	10.5	63.8
March	1274	12.0	88.4
April	1617	13.5	99.8
May	2081	14.7	117.9
June	2250	15.5	120.9
July	2145	15.2	117.5
August	1823	14.0	108.5
September	1383	12.6	91.4
October	855	11.0	64.7
November	500	9.7	42.9
December	403	8.9	37.7

In column (1) the daily total incoming radiation for each month is provided. Average daily incoming radiation includes both radiation in the visible and invisible spectrum with the summer months outshining the winter months in a 5:1 ratio. The average day-length (time period between sunrise and sunset) is given for each month with the shortest day in December (8.8 hrs) and the longest in June (15.6 hrs) with the average day-length changing by 3 minutes/day.

To calculate the average photosynthetically active radiation (PAR) within the greenhouse it is assumed that about 50% of the total radiation is received in the visible spectrum (0.4 to 0.7 microns) and that about 60% is received at plant level in the greenhouse. It should be remembered that these numbers represent the average for the light intensity by dividing the available light by the number of hours of day-length. Actual light intensities increase from sunrise with its maximum at zenith (about noon) after which it decreases to sunset.

During the winter, light is often the limiting factor for greenhouse production. However, the relationship between production and light for greenhouse production is not simple. The following factors should be considered.

Dependence of Carbon Dioxide Assimilation on Duration of Lightcycle and Light Intensity



Graph 1. The relationship between light period or light intensity (PAR) and rate of assimilation (according to Drs. O. Elgersma and Philips, The Netherlands).

It is shown (Graph 1) that the rate of assimilation is directly related to the duration of the light period, i.e. an eight-hour light period will produce twice the amount of assimilation products compared to a four-hour period, provided the lightly intensity is constant. The law of diminishing return is applicable when the rate of assimilation is related to the amount of photosynthetic active radiation, i.e. the advantage of the first 10 W/m^2 is higher than the additional advantage obtained from increasing the light intensity from 20 to 30 W/m^2. This means the the light conversion efficiency is higher for low intensities during the early morning hours than at noon.

The Interaction Between Light Intensity and Plant Leaf

There is an apparent interaction between leaf size and light intensity. This is particularly true for young expanding leaves during periods of low light intensity. Experiments have shown that a reduced light intensity during a certain period is compensated to some degree by a larger leaf surface area, without having an effect on the rate of photosynthesis of these leaves per unit surface area. Larger leaves also mean that light will be better intercepted by the plant to improve the

overall conversion efficiency of the plant. The leaves are usually thin and weak. Leaves formed under high light intensities usually have a thicker cuticle with the chloroplasts being arranged parallel to the sun radiation (inefficient) compared to leaves formed during the low light intensities (chloroplasts perpendicular to sun radiation). Although plants have the ability to adjust to lower light levels, it depends on the age of the plant (= leaves) and the length of time of acclimatization. The above reasoning explains for a large part why spring grown plants are bigger than fall grown plants even though the same amount of light may be received by the plants.

Effect of the Crop Canopy Light is being reflected, absorbed and transmitted by each leaf and only a fraction of the light energy is converted into carbohydrates. The use of several leaves on top of each other will make it more efficient for a crop as a whole (up to 10%). The leaf area index (surface area of leaves per ground area) is for many mature crops about 4-6 m^2/m^2. Also, younger leaves are usually more efficient than older ones in terms of net photosynthesis (gross photosynthesis minus respiration). Growers use that to their advantage by keeping the younger leaves on top (tomatoes and cucumbers) in order to benefit most from the higher light intensity in the top of the canopy.

Although there is a direct relationship between light intensity or a light duration for a single leaf, this is not the case for a whole plant. The effect of the changing environmental factors (Temp., RH, and CO_2) during the season have also a definite effect on the total outcome as well. Although it is difficult to provide numbers for all crops, it is estimated that crop production during the "winter" (Oct. 1 - Apr. 1) is about one-half of that during the "summer" (Apr. 1 - Oct. 1) while the total amount of light received during the "winter" is about one-third of that received during the "summer." Efforts are made by the growers to obtain higher winter production by using high intensity discharge lamps (HID). These lights are used both to extend the day length as well as increase the light intensity during the daytime.

Roses, chrysanthemums, geranium stock plants, African violets, Rieger begonias, carnations, as well as tomatoes and cucumber transplants are often supplemented during the winter months. High pressure sodium lamps (HPS) are the most common source of light. The high conversion factor of electricity into visual radiation as well as its favorable spectral distribution characteristics and longevity of the lamp have contributed to HPS popularity. Different light intensity levels can be applied depending on the specific needs of the crop. Commercial application varies from 20 to 80 W/m^2 installed capacity using HPS lights. An added benefit is a reduction in the fuel bill. Low pressure sodium lights, which have a slightly higher conversion factor than HPS lights, have been tried in various installations but are unsuitable due to the monochromatic light produced. Metal halide lights are often used in Europe to raise tomato and cucumber seedlings during the winter, but their lower energy conversion efficiency and shorter lamp life make them less popular here.

For more detailed information concerning the use of supplemental lights and their application on various crops, see Ontario Ministry of Agriculture and Food Factsheets, *Commercial Applications of Supplementary Lighting in Green-*

houses, and *Supplementary Lighting in Commercial Greenhouses*, Agdex 290/717.

Another form of supplemental lighting applied to greenhouses is for the initiation or prevention of flowering. For short day (SD) sensitive plants (chrysanthemums, Rieger begonias, kalanchoes, poinsettias, etc.) lighting may be installed during the winter to provide a long day regime for the vegetative stage of growth. For long day (LD) sensitive plants (carnations, baby's breath) these lights can be used to initiate the flowering of these plants. Incandescent lights (red light) at an installed capacity of 20 W/m^2 ground area are normally employed. These lights are usually activated between 22.00 and 02.00 hours and provide a light intensity of 70-100 lux at crop level. To save electricity the technique of "cyclic" lighting can be used. This means that the plants are lighted only six of every 30 minutes during the prescribed four-hour period with same results. The above lighting capacity is not considered to be effective for the supplementation of photosynthesis and only to regulate flowering of photoperiodic plants.

4. CONTROLLING THE ENVIRONMENT

Productivity of greenhouse crops depends largely on the proper control of environmental factors such as air, plant, and soil temperatures, relative humidity (RH), carbon dioxide levels, lighting, irrigation, shading, etc.

There are usually three components in the regulation of an environmental factor:

— Controller
— Sensor(s)
— Process Equipment (P.E.)

The sensor measures the actual level of a given parameter (temperature, CO_2, RH) and gives this signal to the controller, which in turn determines whether the process equipment (ventilator, mixing valve, etc.) is to be activated. In general, the level of any given parameter changes in a somewhat sinusoidal way with the aim that the average actual value in the greenhouse is equal to the setpoint of the given parameter. Another important requirement is that the actual value is achieved with minimal operation of the process equipment.

Controllers

The controller is the mid-point and critical decision-maker in the regulation of the environmental factors. An explanation of different controllers is given below and the air temperature (T_a) will be taken as an exemple:

ON/OFF controllers. These units have two signals namely for turning a heater "on" when the temperature is too low and off when the temperature is too high. Most thermostats have a temperature differential (T.D.) which can be set manually. A small T.D. means that the heater runs very frequently but in very short intervals, and a large T.D. means that the heater runs infrequently but for longer periods. The fluctuation of the temperature also depends both on the size of the heating system as well as outside conditions, and the T.D. have to be set for each specific condition(s).

Modulating Controllers. These are used to control a quantity, for instance to control mixing valves in a "pulsating" fashion to prolong the time of correction and to prevent overrides. This is particularly useful in hot water heating systems.

Proportional Controllers. These units provide signals depending on the deviation of the setpoint. The larger the deviation from the setpoint the larger the correction will be (opening of vents/mixing valve). These controllers are often used with mixing valves or pressure regulators. A term which is commonly used with these controllers if the P-band (proportional band). For ventilators this means the temperature range for the windows totally closed and windows totally open. The smaller the P-band, the more the windows will be closed or opened in this temperature range. In practice it would mean that under cold outside conditions a large P-band is advisable and under warm outside conditions a small P-band.

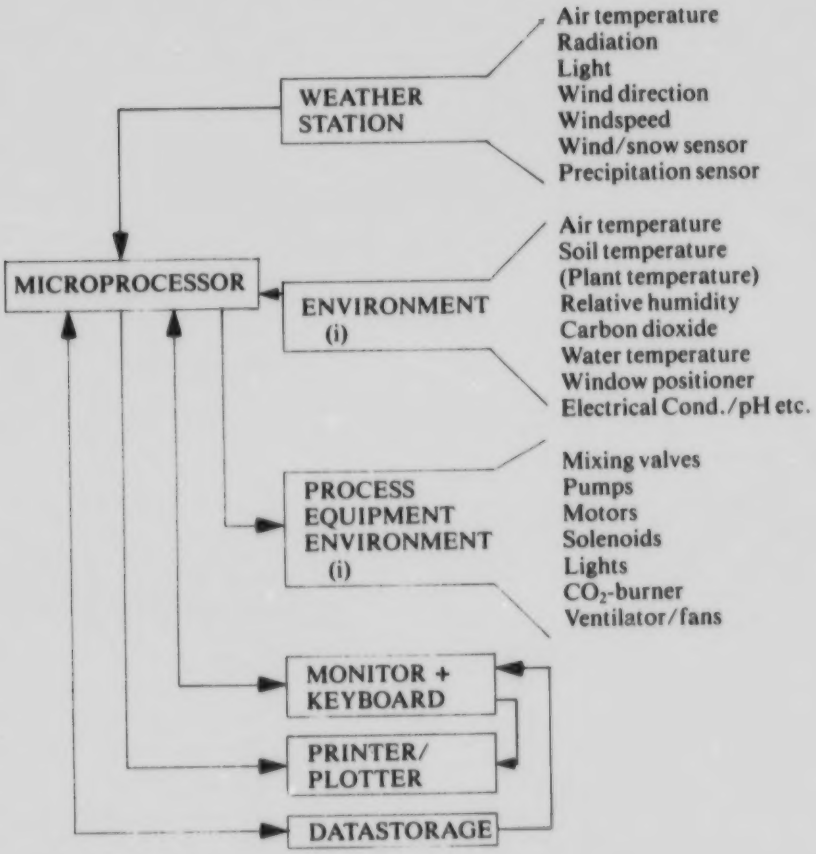
Proportional/Integral (P.I.) Controllers. With proportional controllers it is possible to find a difference between the actual temperature (T_a) and the temperature setpoint (T_s). This difference is called the static deviation. P.I. controllers minimize this by changing the **rate** at which the controller (valve or ventilator) has to change as well. The rate is linearly related to the deviation from setpoint. The larger the deviation from T_s the more pulses for opening or closing a valve. With P.I. controllers the static deviation is to become negligible so that T_a equals T_s.

The P.I. controllers are usually the more sophisticated units and control strategy can depend on outside conditions such as light, windspeed, outside temperature, etc.

Microprocessor Controller. To accommodate a system which can act as a P.I. controller and interacts with all the different options such as light dependent, time dependent, minimum and maximum control of the process equipment, interaction of the different parameters, etc., a microprocessor must be considered. This unit can perform many control functions simultaneously for many environments while the outside conditions are only measured once per sensing cycle. The sensing cycle varies from computer to computer type and also from the control function it has to perform. For climate control a sensing cycle of 20-30 seconds may suffice while the control of the electrical conductivity and pH in the irrigation cycle may require a sensing of every 1-2 seconds. A microprocessor also provides an opportunity to store or print data so that actual values can be compared with the set values.

For a hot water heating system not only the air temperature can be controlled but also the water temperature in the heating lines. The air temperature can be variable relative to sunrise and sunset as well as light dependent and/or dependent on the total daily or weekly radiation sum. The water temperature coming from the boilers as well as entering the heating lines can also be light, ventilation, RH and/or minimum and maximum dependent. If two or more heating groups are installed, each heating system can be independently controlled, so that the systems can run either in series, in parallel or separate from other heating groups with their own setpoint(s).

The possibilities are unlimited and can be made customer-specific. A schematic view of a microprocessor is given in Graph 2.



Graph 2. A schematic view of a microprocessor controller.

There are two basically different set-ups of microprocessor systems for greenhouse climate control. One is a satellite system, and the other one is a centralized system. The satellite system has a small computer system for each or every two environments and does the controlling functions from that point. A central

communication computer provides weather data to the satellites and receives data for storage and/or printout. All the satellites can be hooked up together with one single set of wires which provides the communication. The centralized system brings all the signal inputs and outputs to one point. More wiring is required but service and diagnosis may be easier.

Sensors

When considering the sensing aspect, the conditions under which these sensors operate (high humidity, dust, pesticides, etc.), as well as the parameter(s) sensed must be taken into account.

For each sensing element, accuracy and a short response time are necessary. The latter is important since most parameters change continuously and sometimes very rapidly (injecting fertilizer in irrigation water). For each parameter these are several devices:

Temperature: The mechanical systems include a bimetal (copper/steel), a liquid or a liquid vapor thermostat. All of the above 3 types of thermostats involve the principle that a material expands with increasing temperature.

Other types of sensors which are used in electronic controllers are the ones which change resistance depending on temperature. The most common ones are thermistors. Their sensors are small, durable and show a large change in resistance depending on temperature. Another type are the platinum sensors (PT100 and PT1000) which also change in resistance depending on temperature. Platinum sensors are often used to measure water temperature within a pipe.

Thermocouples are sensors which are made of two conductor wires which are fused at the end. Two wires of different metal are used (e.g. copper/constantan). A voltage difference between the two leads gives an indication of the temperature. In most cases, correction must be made for the resistance in the wires connecting the sensors with the controlling/semsing device.

Relative Humidity: The length dependency of a bundle of hair on the water vapor pressure in the air is often used to measure the relative humidity. This can be through a mechnical means or by changing an electrical resistance. The greenhouse environment with the dust, grease, pesticides, etc., causes a rapid aging of this type of sensor. Continuous cleaning and recalibration is therefore a requirement. Other methods include the measurement of a dry and wet bulb temperature (psychrometer). This method involves a temperature sensor covered with a cotton wick which is kept wet constantly from a distilled water reservoir. Forced air movement (2 m/sec) along the wick causes evaporation from the wick and a reduction in temperature. The degree of temperature reduction relative to that of the dry bulb sensor is used to determine the RH. Psychrometers are used by most manufacturers for microprocessors of greenhouse climate control. Other devices measure changes in resistance due to moisture absorption. Their application is limited in areas where high RH are common.

Carbon Dioxide: The carbon dioxide controllers have become popular during the last 10 years. The principle of measurement is based on the fact that carbon dioxide molecules absorb infrared radiation of a given wavelength range. Air samples from the greenhouse are drawn through the measuring chamber and

compared to the minimum setting. Multiplexers in combination with one sensor are often used to measure the CO_2 level of several compartments. This is done to offset the cost of the infrared sensing device.

Light: There are 3 types of light sensors commonly used in the horticultural industry. The differences are based on the wavelength range measured.

Light Sensors These sensors measure the light photometrically, having the highest sensitivity in the yellow spectrum and tapering down in sensitivity towards the blue and red wavelength regions. The measurements are given either in lux or footcandles (1 foot candle = 10.76 lux).

Radiation Sensors The principle of variable thermal response to radiation of differing wavelength is the basis of radiation measurement. Meteorological stations around the world use Kipp and Zonen sensors to measure the global radiation. These sensors determine incoming solar radiation in the wavelength of 0.2-15 microns. The units are usually in W/m^2 or $J/cm^2/day$. Only part of this radiation (about 50%) is within the visible range (photosynthetically active radiation, PAR) for outside light.

Quantum Sensors Quantum sensors are commonly used by the scientific community in North America. These sensors measure the energy received between 0.4 and 0.7 micron, and imitate the sensitivity of the plants for visible radiation in terms of photosynthesis. As a result a good correlation has been found between plant growth and quanta. The units are in microEinstein per m^2 per sec ($\mu E/m^2/sec$).

Conversion between the different sensors depends largely on the spectral distribution of the light source (Table 9).

Table 9. Conversion of Watts per Square Metre (.4-.85 micron) to Footcandles, to Lux, or to MicroEinsteins per Square Metre per Second (.4-.7 micron) for different light sources

Source	Lux per W/m^2	$\mu E/m^{-2}/s^{-1}$ per W/m^2
Daylight	183	3.4
Incandescent	116	2.3
Fluorescent		
Cool white	334	4.5
Warm white	350	4.6
HID		
Mercury	356	4.2
Metal halide	292	4.1
High pressure sodium	296	3.6
Low pressure sodium	459	4.3

For footcandles divide lux by 10.7

Radiation data developed by R. W. Thimijan.

Figure 15. An aspirated thermostat placed at a representative location.

The sensing elements for temperature and relative humidity should be protected from the influence of outside radiation, and unregulated air currents. Therefore, the sensing elements are to be located in an aspirated box in an appropriate location (Figure 15) in the greenhouse where plant growth takes place. A small fan draws air continuously through the box to provide a more representative sample. Temperature sensors should be calibrated with an accurate thermostat at least twice a year. The carbon dioxide sampling tube(s) should be located within the crop canopy, while light sensors are usually located outside the greenhouse in a non-shaded area.

Process Equipment (PE)

This is the electrical equipment required to make the changes necessary as indicated by the controller. This equipment includes ventilator(s), mixing valve(s), fans, carbon dioxide generators, dehumidifiers, solenoids, etc. The capacity of the PE and the rate at which it operates determines the response time of a given parameter. Slow moving ventilators or mixing valves allow time for the sensors to interreact with the changes occurring within the environment. This is especially important for P.I. controllers, to prevent excessive oscillation of the equipment. Potentiometers are a helpful tool to check ventilator position, mixing valve or shading curtain opening, etc., and are often used in analog and/or microprocessor controllers.

An effective heating and cooling control system should be equipped with overrides and alarms. The overrides can be a manual or an alternate automatic system. If a mechanical malfunction occurs, the heating and cooling systems

should have the capability of hand operation. Backup systems for heating and cooling are a necessity and should be automatically initiated if the temperature drops below a predetermined setpoint. Relative humidity overrides, which activate a combination of heating and ventilation, may also be considered where excessive humidities are anticipated or where extreme humidities are harmful to plant growth. Alarms can take many forms. Alarm systems typically monitor water levels in the boiler, boiler operation and greenhouse temperature. When the system malfunctions an alarm signal can be sent to the operator's residence, can ring a bell or even ring one or many telephones. These alarms should be activated when the override limits are reached. It is important not to set the limits too low or it may be too late to rectify the problem in the greenhouse before crop damage occurs. In addition to alarms or overrides, computers are also used as a recording device that provides a constant record of temperature and possibly relative humidity (Figure 16) which is extremely useful in determining how well the control system is operating.

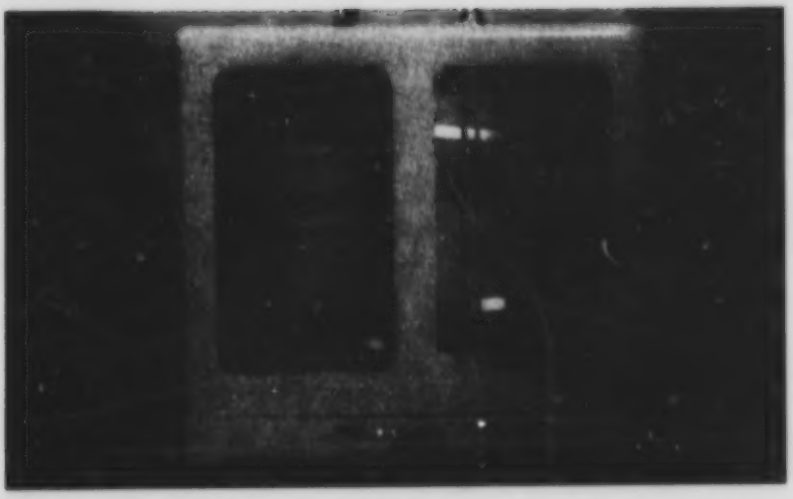


Figure 16. A monitoring system which shows temperature and relative humidity changes over a weekly period.

5. EXPECTED COSTS AND RETURNS

The costs and returns of an average greenhouse operation are difficult to estimate. This is primarily due to the large number of different crops and schedules used by growers in the province. Expenses and revenues are to a large extent determined by the growing cycles (spring only or spring and fall crops) as well as the planting time. Earlier vegetable plantings have higher labour and fuel costs which may be offset by higher yields and prices. A trend with planting in substrates such as rockwool is to plant earlier.

The Ontario Greenhouse Vegetable Producers' Marketing Board acts as the trade organization for the vegetable growers. This board sets minimum prices for vegetable products on a weekly basis. Selling below the minimum levels is illegal. An overview of the Ontario greenhouse vegetable production can be found in the Annual Report from the Board — Box 417, Leamington, N8H 3W5.

If a standard costs analysis is required for greenhouse flower producers the situation is even more confusing. Growers can be generally categorized as a cut flower, potted plant or a bedding plant grower. However, a percentage of flower growers also include a crop of vegetables between the spring and/or fall crop. No marketing analysis exists for cut flowers or potted plants. The Professional Plant Growers' Association (PPGA), P.O. Box 27517, Lansing, Michigan, 48909, published a summary on Bedding Plant Costs of Production in their December 1989 Newsletter.

Marketing of floriculture products is not governed by any legislation. Large growers often act as wholesalers while smaller growers sell to wholesalers or through the "flower auction" (Ontario Flower Growers' Cooperative Ltd.) in Mississauga.

A comprehensive, up-to-date, numerical description of the greenhouse industry is provided in the annual report *Agricultural Statistics for Ontario*, Publication 20 or in the annual report by Statistics Canada, Catalogue 22-202, *Greenhouse Industry*. This latter survey has been conducted since 1955 and is primarily pertinent to market structure and production inputs and outputs for the whole industry.

6. SOURCES OF GREENHOUSE SUPPLIES

PAUL BOERS
P.O. Box 134, Regional Road #81
St. Davids, Ontario L0S 1P0
Tel: 416-262-4911 Telex 061-5344
416-262-5122

- Greenhouse Manufacturing and Maintenance

BRINKMAN HORTICULTURAL INC.
11 Commerce Court
Stoney Creek, Ontario L8E 4G3
Tel: 416-643-6630
Fax:416-643-6858

- Fertilizer sets
- Climate control computers
- Greenhouse supplies and equipment

CAMPBELL, O'BRIEN LTD.
#1 Thompson Crescent
Erin, Ontario N0B 1T0
Tel: 519-833-9628
Fax: 519-833-9620

- Greenhouses
- Greenhouse Benching Systems

CAN. GENERAL ELECTRIC PLASTICS
2300 Meadowvale Boulevard
Mississauga, Ontario L5N 5P9
Tel: 416-620-2400
Toll Free: 1-800-268-2600

- Lexan Thermoclear Sheet

CANADIAN HYDROGARDENS LTD.
411 Book Road West
Ancaster, Ontario L9G 3L1
Tel: 416-648-1801 Telex: 061-8426
Fax: 416-648-1870

- Greenhouse computer and irrigation systems
- Horticultural growing supplies
- Fertilizers/seeds/substrate

CRAVO EQUIPMENT LTD.
White Swan Road, R.R. #1
Brantford, Ontario N3T 5L4
Tel: 519-759-8226
Fax: 519-752-0082

- Exterior Retractable Shading, Cooling and Frost Protection Curtain Systems
- Greenhouse Blackout, Shading/Cooling and Heat Retention Curtain Systems

DeCLOET GREENHOUSES
R.R. #1
Simcoe, Ontario N3Y 4J9
Tel: 519-582-3081

- Greenhouse manufacturer

DJON ENTERPRISES LTD.
P.O. Box 551, R.R. #1
Mitchell, Ontario N0K 1N0
Tel: 519-348-8483
Fax: 519-348-9551

- Dosatron Injectors
- Aquacel Evaporative Cooling

W. R. GRACE & CO. OF CANADA LTD.
294 Clements Road West
Ajax, Ontario L1S 3C6
Tel: 416-683-8561 Telex: 06981 451
Fax: 416-683-5947

- Fertilizers
- Amendments
- Soilless Mixes

GROWERS GREENHOUSE SUPPLIES
P.O. Box 83
Vineland Station, Ontario
Tel: 416-562-7341

- Manufacture greenhouses
- Coverings — poly, polycarb, acrylic
- Ventilation equipment

GROWERS REQUISITES LTD.
1738 Highway 18E
Kingsville, Ontario N9Y 2M6
Tel: 519-326-4466
Fax: 519-326-8038

- Brookside Consulting Service
- Roof Vented Poly Houses
- Terragas 67 Soil Fumigation

GROWERS TECHNICAL SERVICES LTD.
2241 Dunwin Drive
Mississauga, Ontario L5L 1A3
Tel: 416-828-5925 Telex: 065-22418

- Greenhouse computers and control equipment
- Greenhouse irrigation systems
- Fertilizer mixers

GREENHOUSE SUPPLIES (continued)

HAKMET LTD.
881 Harwood Boulevard, P.O. Box 248
Dorion, Quebec J7V 7J5
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Fax: 514-455-1890

- Lannen Plant Systems with Automatic Transplanting
- Paperpot System
- Lannen Ecopot System

HORTICON SYSTEMS LTD.
263 Huntingdon Avenue
Stratford, Ontario N5A 6P7
Tel: 519-273-7810
Fax: 519-273-7810

- Portable pH and EC, Humidity and Light meters
- Fertilizer Injection Systems
- pH Correction Systems

JACOBS GREENHOUSE MANUFACTURING LTD.
371 Talbot Road
Delhi, Ontario N4B 2A1
Tel: 519-582-2880
Fax: 519-582-4117

- Greenhouse Manufacturing
- Reskin/Reglazing
- Rolling/Stationary Benches

FRANK JONKMAN & SONS LIMITED
R.R. #4
Bradford, Ontario L3Z 2A6
Tel: 416-775-5353
Fax: 416-775-4785

- Complete Greenhouse Systems
- Heating Systems, Ventilation
- Environmental Controls

KEATING METAL MANUFACTURING LTD.
Box 1201
Stirling, Ontario K0K 3E0
Tel : 613-395-2819
Fax: 613-395-0381

- Carts
- Wagons
- Advertising Stands

KEYTECH WATER MANAGEMENT INC.
16 - 20 Steckle Place
Kitchener, Ontario N2E 2C3
Tel: 519-748-5298
Fax: 519-748-5026

- Water Treatment Chemicals
- Metering and Control Equipment

LANDER CONTROL SYSTEMS INC.
129A Watson Road South
Guelph, Ontario N1H 6H8
Tel: 519-824-1172

- Computerized Environment Control System

LEADER FAN INDUSTRIES LIMITED
130 Clairville Drive
Rexdale, Ontario M9W 5Y3
Tel: 416-675-4700
Fax: 416-675-4707

- Greenhouse Fans
- Shutters
- Inflation Kits

MACO ENTERPRISES
R.R. #2
Drayton, Ontario N0G 1P0
Tel: 519-638-2746

- Forced air wood pellet fired furnace
- Wood pellet fired burners
- Custom designed burners

MYKRON GREENHOUSE TECHNOLOGY
50 Hazelton Street, P.O. Box 33
Leamington, Ontario
Tel: 519-326-9037

- Agriculture Chemicals
- Mykron System

NIAGROW SYSTEMS INC.
6A Hiscott Street
St. Catharines, Ontario L2R 1C6
Tel: 416-641-2600
Fax: 416-641-3497

- Sales and Design Complete Hot Water and Steam Heating Systems
- Complete Ground Cooling Systems
- Boiler Room Systems with Gas, Oil or Waste Burning

NIARTEC INC.
6A Hiscott Street
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Tel: 416-641-2800
Fax: 416-641-3497

- Complete Irrigation Systems Ebb & Flow, Drip, NFT.
- Computer or Analog Environment Control Systems
- Fertilizer and pH Injection Systems

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P.O. Box 206, 183 South Service Road
Grimsby, Ontario L3M 4G3
Tel: 416-945-4133
Fax: 416-945-0444

- H.I.D. growlights

PLANT PRODUCTS CO. LTD.
314 Orenda Road
Brampton, Ontario L6T 1G1
Tel: 416-793-7000 Telex: 06-97595
Fax: 416-793-9157

- Fertilizers — Water Soluble and Controlled Release
- Pesticides — Crop Protection Products
- Greenhouse Supplies

PLANTECH CONTROL SYSTEMS
3466 South Service Road, P.O. Box 800
Vineland Station, Ontario L0R 2E0
Tel: 416-562-7345
Fax: 416-562-5958

- Priva Horticultural Computers
- Electrical Installations
- CO_2 Meters, Burners, Circulation Fans

PLASTOMER INC.
151 John Street, P.O. Box 14000
Barrie, Ontario L4M 4V3
Tel: 705-726-0225

- Seedling Trays
- Plastic Containers

PREMIER PEAT MOSS LTD.
53 Estate Drive
Scarborough, Ontario M1H 2Z2
Tel: 416-431-5936
Fax: 416-431-5466

- Peat Moss
- Pro-Mix
- Perlite-Vermiculite-Bark

M.K. RITTENHOUSE & SONS LTD.
R.R. #3, Fourth Avenue
St. Catharines, Ontario L2R 6P9
Tel: 416-684-8122
Fax: 416-684-1382

- Greenhouse Sprayers
- Spray Accessories

ROGER CONTROL SYSTEMS INC.
P.O. Box 231
Hannon, Ontario L0R 1P0
Tel: 416-383-6771

- Spraying Equipment
- Electrical Control Panels
- Electrical Contracting

ROYAL PURPLE GARDEN SUPPLIES
359 Ridout Street North
London, Ontario N6A 4G3
Tel: 519-432-2653

- Fisons Peat Moss

SAFER LTD.
465 Milner Avenue, Unit #1
Scarborough, Ontario M1B 2K4
Tel: 416-291-8150
Fax: 416-291-1755

- Biological Control
- Natural Insecticides and Fungicides
- Natural Plant Management Products

SHAMROCK INDUSTRIES
P.O. Box 730, Highway 59 South
Norwich, Ontario N0J 1P0
Tel: 519-468-3024

- Speedel Soilless Premix Media

SHEMIN NURSERIES INC.
R.R. 4
Milton, Ontario L9T 2X8
Tel: 416-878-0587

- Irrigation Systems

SMITHERS-OASIS
108 McMaster Avenue
Ajax, Ontario L1S 2E7
Tel: 416-683-0750 Telex: 06-986804
Fax: 416-683-9163

- Oasis®-Rootcubes®-Growing Medium
- Oasis® LC-1 Horticubes
- Oasis® Wedge™-Growing Medium

THE ST. GEORGE COMPANY
St. George, Ontario N0E 1N0
Tel: 519-442-2046

- Kasco protective helmets
- Grilling walk behind tractors

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Burlington, Ontario L7N 3H8
Tel: 416-632-8503
Fax: 416-632-2833

- Liquid Handling Equipment
- Poly Tanks, Fittings, Pumps
- Micronutrients

SUBMATIC IRRIGATION SYSTEMS
25 West Beaver Creek Road, Unit 10
Richmond Hill, Ontario L4B 1K4
Tel: 416-764-9121
Fax: 416-764-1468

- Drip Irrigation Systems
- Misting Systems

C.N. SUTER LIMITED
R.R. #4
Hagersville, Ontario N0A 1H0
Tel: 416-768-5466
Fax: 416-768-5466

- Greenhouse Sprayers
- Indoor Plant Care Carts
- Greenhouse Carts

GTE SYLVANIA CANADA LIMITED
2001 Drew Road
Mississauga, Ontario L5S 1S4
Tel: 416-673-6171
Fax: 416-673-1413

- Horticultural Lamps
- Fluorescent Fixtures for Horticulture
- H.I.D. Fixtures for Horticulture

TNT STAND-BY POWER
150 Thames Road East
Exeter, Ontario N0M 1S3
Tel: 519-235-2364
Fax: 519-235-1203

- Generators
- Agricultural Sprayers
- Chain Lifts

VANDENBUSSCHE IRRIGATION
970 James Street
Delhi, Ontario N4B 2X1
Tel: 519-582-2380

VANDER DUSSEN GREENHOUSES INC.
5327 5th Line, R.R. 4
Milton, Ontario L9T 2X8
Tel: 416-875-1919

- Danish Style Bedding Plant Carts
- Azaleas

VANHOF AND BLOKKER LTD.
6745 Pacific Circle
Mississauga, Ontario L5T 1S6
Tel: 416-670-2852
Fax: 416-670-2889

- Flowerbulbs
- Perennials and Cuttings
- Greenhouse Supplies

JACK VAN KLAVEREN LTD.
P.O. Box 910, Seventh Street
St. Catharines, Ontario L2R 6Z4
Tel: 416-684-1103 Telex: 061-5221
Fax: 416-684-6260

- Seed Annuals, Vegetable, Pot Plant and Perennial
- Rooted and Unrooted Plant Material for Growing On
- Greenhouse Supplies and Equipment

VARY INDUSTRIES (1982) LTD.
317 South Service Road
(East of Casablanca Boulevard)
P.O. Box 160
Grimsby, Ontario L3M 4N6
Tel: 416-945-9691
Fax: 416-945-2313

- Greenhouses
- Benches
- Root Zone Heating

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Publications 1, 2, 3, 5, 6, 7, 9, 10, can be obtained from your county office or from the Information Branch, Ontario Ministry of Agriculture and Food, 801 Bay Street, Toronto, Ontario M7A 1A5.